APR 22 '44 F

Volume 14 APRIL, 1944 Number 1

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

« CONTENTS »

Significance of Texture and Density of Alluvial Deposits in the Middle Rio Grande Valley ..... *Stafford C. Happ* 3

Errors of Sampling Sands for Mechanical Analysis ..... *Gordon Rittenhouse and Mark P. Connaughton* 20

Beach Markings Made by Sand Hoppers ..... *K. O. Emery* 26

Petrology of the Pennsylvanian Cycles of the Saint Louis Area ..... *Albert J. Frank* 29

REVIEW

C. B. Brown, The Control of Reservoir Silting ..... *W. H. Twenhofel* 39

Journal of Sedimentary Petrology

W. H. TWENHOFEL, EDITOR
Madison, Wisconsin

ASSOCIATE EDITORS

W. C. KRUMBEIN
Chicago, Illinois

M. N. BRAMLETTE
Los Angeles, California

HENRY B. MILNER
London, England

CLARENCE S. ROSS
Washington, D.C.

R. DANA RUSSELL
University, Louisiana

The *Journal of Sedimentary Petrology* is published by the Society of Economic Paleontologists and Mineralogists, a division of The American Association of Petroleum Geologists. Numbers are issued in April, August and December.

The subscription price of the *Journal of Sedimentary Petrology* is $3.00 per year prepaid to addresses in the United States.

Single numbers, $1.50 each.

Postage is charged extra for all other countries: 40 cents on annual subscriptions (total $3.40).

The *Journal* will furnish reprints at cost. Orders should accompany corrected galley proof.

Communications about the *Journal*, subscriptions, rates, memberships, change of address, advertising and non-receipt of preceding numbers should be addressed to Society of Economic Paleontologists and Mineralogists, P.O. Box 979, Tulsa, Oklahoma. Claims for non-receipt of preceding numbers must be sent in within three months of the date of publication in order to be filled gratis.

Communications in regard to manuscripts or purely editorial matters should be addressed to W. H. Twenhofel, Editor, University of Wisconsin, Madison, Wisconsin.

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN, U.S.A.

Volume 14 APRIL, 1944 Number 1

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

CONTENTS

Significance of Texture and Density of Alluvial Deposits in the Middle Rio Grande Valley ..... *Stafford C. Happ* 3

Errors of Sampling Sands for Mechanical Analysis ..... *Gordon Rittenhouse and Mark P. Connaughton* 20

Beach Markings Made by Sand Hoppers ..... *K. O. Emery* 26

Petrology of the Pennsylvanian Cycles of the Saint Louis Area ..... *Albert J. Frank* 29

REVIEW

C. B. Brown, The Control of Reservoir Silting ..... *W. E. Twenhofel* 39

NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 14, NO. 1, PP. 3–19
FIGS. 1–5, TABLES 1–2, APRIL, 1944

SIGNIFICANCE OF TEXTURE AND DENSITY OF ALLUVIAL DEPOSITS IN THE MIDDLE RIO GRANDE VALLEY

STAFFORD C. HAPP
Soil Conservation Service, Washington, D. C.

ABSTRACT

Mechanical analyses of representative samples indicate that alluvial deposits accumulated in the Middle Rio Grande Valley, during the period 1936–41, had an average composition of approximately 43% sand, 41% silt, and 16% clay according to the Wentworth size grades. The median grain size was about 0.054 mm., which is in the coarsest silt size of the Wentworth classification or in the very fine sand size of the soils classification of the Department of Agriculture. Corresponding determinations of the sediment density (dry weight per unit volume) indicate an average density of about 86 pounds per cubic foot for the median grain size of all the deposits, about 85 pounds per cubic foot for the overbank flood-plain deposits, and 100 pounds per cubic foot for the river-bed sediment. The results lend support to the use of sand sizes as criteria of the sources of all sediment in the Valley. The textural data also indicate that sand accumulation along the Rio Grande is due to excessive supply from tributary sources rather than lag accumulation; that channel avulsions and "splay" deposits of sand on the flood plain are major factors in the river regime; and that extension of the textural studies might provide a useful measure of the relative importance of different erosional processes. In combination with other available data, the density determinations provide a basis for estimating the entire rate of sediment output, or net erosion, from the drainage basin above Elephant Butte Reservoir, which is at the lower end of the Middle Valley. This rate is indicated as 0.7 acre-foot per square mile for the period 1936–41, equivalent to an average rate of surface lowering of 1 inch in about 75 years. Other studies indicate that this 5-year rate is probably somewhat lower than the average for a period of 15 to 25 years.

INTRODUCTION

The Middle Rio Grande Valley, a reach of alluvial lands about 150 miles long and 2 miles in average width in central New Mexico, has one of the most serious sedimentation problems in the United States. The river is at or above the level of adjoining irrigated flood-plain lands in many places, and evidently is aggrading throughout most of the Valley. This creates a serious flood hazard and holds the ground-water table so high beneath the alluvial lands that their productivity is impaired, and continued effectiveness of drainage ditches required to prevent waterlogging and excessive alkali accumulation is in doubt. Sand accumulation is apparently an important factor and, perhaps, the controlling factor in the river aggradation. The normal or unvegetated river channel is about a quarter-mile wide, on the average, but water depths seldom exceed 10 feet and at ordinary stages most of the river bed is a dry sand flat. Only in the upper 20 miles of the Valley is gravel an important part of the upper few feet of river-bed sediments, although it is present at greater depths throughout most of the Valley and probably is moved and accumulated to some unknown extent during major floods. Finer sediment is deposited overbank, but a considerable part of the finer sizes go on into Elephant Butte Reservoir, immediately below the Middle Valley, where the resulting loss of water-storage capacity constitutes another serious sedimentation problem.

Several factors have combined to cause the river aggradation and excessive sediment accumulation in the Middle Rio Grande Valley. The normal downstream decrease in stream gradient is accentuated because of a corresponding decrease in volume of surface flow, due to high evaporation and percolation rates which dissipate more water than is brought in by tributaries from the adjacent semiarid

territory. Large diversions of water for irrigation farther upstream, particularly in the San Luis Valley of southern Colorado, have aggravated these conditions. Backfilling from the delta of Elephant Butte Reservoir has, undoubtedly, accelerated the rate of sedimentation at the lower end of the Valley, although

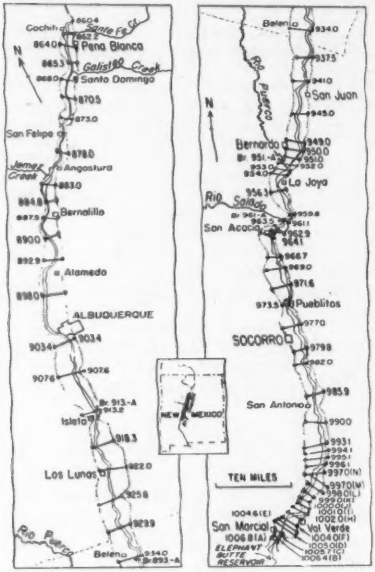

FIG. 1.—Map of Middle Rio Grande Valley, showing valley cross-section ranges (some ranges omitted for clarity).

available evidence indicates that this was an area of relatively rapid sedimentation and river aggradation even prior to the Reservoir construction. Overgrazing of range lands drained by the lateral tributaries, all of which are ephemeral or intermittent streams, has accelerated rates of soil erosion, and particularly of arroyo growth, so that the sediment loads delivered to the Rio Grande have been greatly increased even as the volume of water available to transport the sediment has been decreased by irrigation uses. The aggradation may have been in process for many centuries under natural conditions, but the present high rates, which are the cause of immediate concern, appear to be the result of human activities within the past three-quarters of a century.

Since 1936 the Soil Conservation Service has carried on surveys and research studies to provide reliable information on the sedimentation conditions in connection with planning remedial conservation measures for the lands from which most of the sediment is derived. Comparative surveys on a series of cross-section lines indicated an average accumulation of about 12,000 acre-feet of sediment per year for the period 1936–41. Throughout all but the lower 14 miles of the Middle Rio Grande Conservancy District levees confine most overflows within a floodway about twice the average river width. Approximately 25% of the 1936–41 accumulation was in this floodway which was aggraded at an average rate equivalent to about 1 foot in 12 years. During the floods in 1937 and 1941 the levees were washed out in a number of places, and about 20% of the total sediment accumulation occurred in places flooded because of these levee failures. The remaining 55% of the sediment was concentrated in the lower 14 miles of the Valley, where no adequate levee system existed and deposition was general over the entire flood plain. Here the average rates of flood-plain and river aggradation were about twice those in the floodway, but several channel avulsions and associated local channel incision complicate the picture and, probably, the rates indicated are higher than are likely to be maintained over a longer period. Throughout the floodway there was little net change in the river-bed elevation, but this is believed to be a temporary condition due to a major flood which scoured the bed shortly prior to the 1941 surveys. Less complete data indicate that the average rate of river-bed aggradation, since about 1918, has been essentially the same as the rate found for the floodway as a whole during the 1936–41 period,

and these relations, probably, can be expected to hold in the future also.[1]

Correlation of the data on volumes and distribution of sediment with erosional data, and with rates of sedimentation in Elephant Butte Reservoir, requires information also on the texture and apparent density[2] of the Valley deposits. Data on the texture of the river-bed materials were also required as part of a special study of the mineralogical composition, carried on by Dr. Gordon Rittenhouse for evaluation of the major tributary sources of the sands. Details of the data on river-bed samples are being presented in his separate report on the mineralogical studies.[3] For density determinations, and to represent the texture of overbank deposits, 56 additional samples were collected in 1941 and analyzed by Richard G. Grassy with results as summarized in table 1. The data should be of value for comparative studies in other regions, and they also provide a basis for several significant conclusions of both local and general importance.

METHODS OF SAMPLING

Samples for density determinations, which are designated as spot samples in table 1, were collected with a steel sampling tube 2 inches long and 6.02 inches in average diameter. The relatively large diameter and short length were chosen to reduce errors of compaction and disturbance by frictional drag inside the tube, and to allow collection of representative samples from sediment that had been cracked in drying. The side walls were one-tenth inch thick at the top and tapered on the outside to a cutting edge at the bottom.[4] The tube was forced vertically into the sediment by tapping with a hammer until the upper edge was slightly below the surface of the sediment. Sediment surrounding the outside of the tube was then removed with a putty knife to a depth several inches below the base of the tube. The column of sediment thus isolated, including that outside the tube, was lifted out of the small pit on a shovel and placed on a clean paper. Sediment adhering to the outer side of the tube was scraped off and the core carefully trimmed flush with the ends of the tube by use of a long, broad-bladed knife pressed against the edge of of the tube. The core then remaining inside the tube was transferred to a paper bag and this shipped in a canvas bag to the laboratory where the sediment was dried and weighed. A mechanical analysis was also made as a basis for comparison with the composite samples on which textural data alone were obtained. The samples were chosen to represent the apparent range both of sediment texture and of compaction by drying in the deposits of important volume throughout the Valley.

Composite samples representing the average texture of overbank deposits were composed of four to ten vertical cores collected at approximately equal intervals on a line across the floodway, across the flood plain below the Conservancy District, or across the areas of deposition outside levee breaks. The number of vertical cores was varied according to the width of the area sampled and the depth of sediment, in order to make a composite sample of convenient size, usually between 3 and 4 pounds. Cores were taken with a 1¾-inch screw-type

[1] Happ, Stafford C., "Sedimentation in the Middle Rio Grande Valley, New Mexico." Unpublished; manuscript in files of the Soil Conservation Service.

[2] Apparent density, or volume-weight ratio, is expressed for this report in pounds of dry sediment per cubic foot of sediment in place. For convenience, it will subsequently be referred to simply as "density." "Specific weight" is a synonymous term having the support of authority, but has not come into common usage in sedimentation literature.

[3] Rittenhouse, Gordon, "Sources of Modern Sands in the Middle Rio Grande Valley, New Mexico." To be published in the Journal of Geology.

[4] Curry (1931) has shown that more consistent density determinations are obtained for such alluvial soils, if a cylinder of large diameter is used for collection. For the present study the type of cylinder used by Curry was considerably modified to fit the range of field conditions.

TABLE 1. *Density and mechanical composition*

Sample No.	Type of sample	Locality	Density	>1.981 mm.	1.981 to 1.397 mm.	1.397 to 0.991 mm.	.991 to .701 mm.	.701 to .495 mm.	.495 to .351 mm.	.351 to .246 mm.	.246 to .175 mm.	.175 to .124 mm.
			Lbs./cu. ft.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
35	Spot	Range 860.4, river bar	101.0		0.2	0.4	1.2	4.7	13.7	24.2	24.[illegible]	2[illegible]
36	Composite	Range 860.4, floodway		3.9	0.4	0.5	0.6	0.8	1.7	5.4	8.[illegible]	1[illegible]
37	Composite	Range 873, west overflow area		0.5	0.4	1.7		7.7		17.5		
38	Composite	Below Angostura Diversion, floodway			0.1	0.3		1.8		12.1		
39	Composite	Below Alameda Bridge, floodway						0.2		9.3		
40	Composite	Range 907.6, west 1200′ of valley		2.0	1.4	5.0		13.8		17.1		
41	Composite	Range 907.6, 1000′ west from highway			0.2	0.9		6.5		14.8		
42	Composite	Range 907.6, 1000′ west from floodway				0.3		1.0		7.6		
43	Composite	Range 907.6, floodway				0.1		1.0		12.9		
44	Spot	Range 907.6, east floodway	86.1		0.1	0.1		0.1		0.3		
45	Composite	Range 922, floodway			0.3	0.1		0.4		4.9		
46	Spot	Range 922, floodway	86.9		TR.	TR.		0.1		0.3		
47	Spot	Range 922, floodway	73.2									
48	Composite	Range 934, floodway			0.1	0.2		1.2		5.0		
49	Composite	Bosque Bridge, floodway			0.0	0.2		2.4		13.5		
50	Composite	Range 945, east overflow area				0.1		0.5		4.3		
51	Spot	Range 945, east overflow area	103.5		TR.	0.0	TR.	0.1	0.1	1.1	6.[illegible]	28
52	Spot	Range 945, east overflow area	81.7									
53	Composite	Range 949, west overflow area			0.1	0.4		6.4		20.1		
54	Spot	Range 949, west overflow area	76.4									
55	Spot	Range 949, west overflow area	90.3	0.0	0.0	0.8	0.2	0.6	1.3	4.5	11.[illegible]	17
56	Composite	Range 949, floodway			0.0	0.1		0.3		5.0		
57	Composite	Range 949, east overflow area								0.5		
58	Spot	Range 949, east overflow area	79.6									
59	Spot	Range 949, river bar	102.0		0.0	TR.	0.1	0.2	0.8	3.7	17.[illegible]	32
60	Composite	Range 951, floodway					TR.	0.1		0.8		
61	Spot	Range 951, floodway	87.0		0.3	0.2	0.2	0.2	0.1	0.5	2.[illegible]	16
62	Spot	Range 951, floodway	73.0									
63	Composite	Range 951, west overflow area										
64	Composite	Range 954, floodway							0.9		10.0	
65	Composite	Range 966.7, west overflow area			0.1	0.1			1.1		10.5	
66	Spot	Range 966.7, west overflow area	83.1		TR.	0.1	0.1	0.4	1.2	5.6	18.[illegible]	34
67	Spot	Range 966.7, west overflow area	91.4			0.0		0.1		0.3		
68	Composite	Range 966.7, floodway						0.2		2.4		
69	Spot	Range 966.7, floodway	80.2		TR.	0.1	0.1	TR.	TR.	0.1	0.[illegible]	1
70	Spot	Range 966.7, river bar	98.0		0.0	TR.	0.2	1.2	9.3	40.6	28.[illegible]	12
71	Composite	Range 971.6, west overflow area								3.5		
72	Spot	Range 971.6, west overflow area	87.0						TR.	1.8		
73	Spot	Range 971.6, west overflow area	48.3									
74	Composite	Range 973.5, east overflow area							0.2		0.9	
75	Composite	Range 990.9, west overflow area			0.0	0.1			0.1		1.7	
76	Composite	San Antonio Bridge, floodway									0.4	
77	Spot	San Antonio Bridge, floodway	94.2									
78	Spot	San Antonio Bridge, floodway	81.4								0.3	
79	Spot	San Antonio Bridge, river bar	101.2		0.0	0.0	TR.	0.1	0.0	0.2	1.[illegible]	14
80	Spot	San Antonio Bridge, floodway	88.5									
81	Composite	Range 997(M), west overflow area							0.2		1.9	
82	Composite	Range 997(M), east overflow area			0.0	0.1			0.1		1.5	
83	Spot	Range 998(L), east overflow area	80.8									
84	Composite	Range 1001(I) overflow area			0.0	TR.	0.1	0.1	0.3	1.0	4.[illegible]	18
85	Spot	Range 1002.4(2), east overflow area	78.6									
86	Composite	Range 1004(F), east overflow area							0.1		1.3	
87	Composite	Range 1005.7(C), west of railway										
88	Composite	Range 1006.8(A), overflow area			0.0	TR.			0.2		3.8	
89	Spot	Range 1006.8(A), west overflow area	78.5						0.0		0.1	
90	Spot	Range 1006.8(A), west overflow area	80.9		TR.	0.1	0.1	TR.	0.1	0.1	0.[illegible]	1.[illegible]

soil auger, and in most places each core represented the approximate depth of sediment deposited since 1936, as known from cross-section surveys, or from identification of sod known to have been covered by sediment in 1937 or 1941. In a few places the deposits were so thick that it would have made the samples unduly bulky to collect the entire vertical core, and here only a proportional part was retained from each individual vertical sequence. In such places only every second or third 6-inch auger core, as taken from the boring, was retained for the sample. Three composite samples, each composed of six vertical cores representing the upper 8 inches of the sediment or soil, were also taken

DUE TO POOR BINDING, SEVERAL PAGES DID NOT PHOTOGRAPH WELL. THIS REPRODUCTION IS MADE FROM THE BEST COPY AVAILABLE.

DUE TO POOR BINDING, SEVERAL PAGES DID NOT PHOTOGRAPH WELL. THIS REPRODUCTION IS MADE FROM THE BEST COPY AVAILABLE.

of Middle Rio Grande Valley sediment samples

Mechanical composition by grade sizes															
.175 to .124 mm.	.124 to .088 mm.	.088 to .061 mm.	.061 to .0312 mm.	.0312 to .0156 mm.	.0156 to .0078 mm.	.0078 to .0039 mm.	.0039 to .00195 mm.	.00195 to .00098 mm.	.00098 to .00049 mm.	>0.061 mm.	<0.061 mm.	<.00195 mm.	<.00098 mm.	<.00049 mm.
Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
20.1	7.1	1.9								97.8	2.2			
15.8	13.0	7.1	25.4	6.7	2.7	1.4	1.1			57.8	42.2	4.9		
18.6		5.5	25.7	7.0	3.6	2.2	2.3			51.9	48.1	7.4		
29.3		7.5	25.1	10.3	4.5	1.7	1.8			51.1	48.9	5.5		
16.6		3.3	18.2	16.7	12.2	6.2	3.8	3.1	3.1	29.4	70.6			7.3
13.7		3.2	12.2	5.2	3.6	3.1	3.1	3.1	4.5	54.2	43.8			9.0
15.2		4.5	21.4	6.2	4.6	4.2	4.1	4.6	4.8	42.1	57.9			8.0
15.9		4.6	16.9	8.2	8.2	6.3	5.0	5.5	5.3	29.4	70.6			15.2
23.6		3.2	21.5	16.0	8.9	3.2	1.8			40.8	59.2	7.8		
4.4		6.2	66.8	12.0	3.1	0.9	0.9			11.2	88.8	5.1		
35.5		7.2	21.3	9.8	6.3	4.1	1.4			48.4	51.6	8.7		
21.4		11.2	39.5	15.5	5.1	1.4	0.9			33.1	66.9	4.5		
			8.7	33.3	27.5	10.0	5.2	4.9		1.7	98.3	8.7		
12.8		5.3	37.2	10.0	5.5	3.8	3.4	2.8	3.9	24.6	75.4			8.8
29.7		4.0	11.7	4.5	4.5	4.6	4.5	4.5	4.9	49.8	50.2			11.0
25.2		9.8	30.6	12.2	5.5	2.3	1.8			39.9	60.1	7.7		
28.2	24.4	11.2	21.8	2.9	1.0	0.5	0.6			71.2	28.8	2.0		
2.1		2.0	23.9	27.4	25.8	8.0	3.1			4.1	95.9	7.7		
28.4		5.8	10.4	4.2	4.3	3.6	2.5	3.7	3.1	61.2	38.8			7.0
			3.2	35.5	36.8	11.3	3.5			1.2	98.8	8.5		
17.3	15.1	8.4	23.8	5.7	1.9	1.9	0.9			59.6	40.4	6.2		
25.5		7.1	24.1	11.0	8.1	4.4	3.4			38.0	62.0	11.0		
5.6		2.2	17.4	18.5	19.8	11.7	5.8	4.7	3.9	8.3	91.7			9.9
			10.5	32.4	32.4	9.6	2.7	2.4		2.3	97.7		7.7	
32.0	20.2	8.1								82.8	17.2			
19.5		9.0	26.7	13.8	9.6	5.3	2.9	2.9		29.4	70.6		9.4	
16.5	29.2	15.4	28.8	2.0	0.7	0.6	0.5			65.0	35.0	2.4		
			2.0	11.9	25.9	21.6	11.6	8.8	7.5	0.5	99.5			10.2
10.7		3.3	16.1	11.4	11.3	9.6	7.5	7.2	6.3	14.0	86.0			16.6
13.5		4.6	17.3	7.8	6.1	6.2	4.9	6.0	5.5	29.0	71.0			17.2
23.9		8.0	28.1	8.6	4.6	3.0	2.6			43.7	56.3	9.4		
34.6	21.9	7.6								90.0	10.0			
11.5		7.9	52.6	13.2	4.6	1.6	1.0			19.8	80.2	7.2		
12.6		5.1	29.8	15.9	9.2	2.6	5.1	2.6	4.1	20.3	79.7			10.4
1.6	13.3	15.0	56.9	3.7	1.0	1.0	0.7			30.3	69.7	6.4		
12.4	3.5	1.2								97.3	2.7			
6.5		2.1	16.6	14.2	15.5	10.2	6.1	5.5	4.9	12.1	87.9			14.9
22.9		2.7	5.6	11.0	16.4	13.0	6.5	5.3	4.8	27.4	72.6			10.0
			0.0	0.8	6.1	12.6	14.7	18.7	18.4	0.2	99.8			28.5
13.7		5.7	27.1	13.8	8.1	5.4	4.2	4.3	4.4	20.5	79.5			12.2
28.8		10.6	34.2	11.0	4.3	1.8	1.3			41.3	58.7	6.1		
6.9		2.9	20.9	10.7	8.2	7.3	7.4	7.1	7.3	10.2	89.8			20.9
			0.3	0.8	4.1	11.7	18.8	24.0	19.9	0.2	99.8			20.2
1.8		3.2	45.2	22.7	9.0	3.8	2.9	2.3		5.3	94.7		8.8	
14.5	25.6	14.4	33.4	4.1	0.9	1.2	1.0			55.8	44.2	3.6		
			25.9	32.9	18.3	6.6	3.2	1.8	3.8	1.0	99.0			6.5
13.9		5.6	16.3	4.1	7.2	9.9	8.6	6.8	6.8	21.6	78.4			18.7
18.4		8.3	47.5	10.5	4.0	1.6	1.7			28.4	71.6	6.3		
			0.7	13.3	30.1	21.0	9.9	6.6	6.3	0.3	99.7			11.8
18.4	25.0	11.4	21.8	3.9	2.7	2.4	1.7			60.8	39.2	6.7		
			11.1	22.0	20.7	9.9	6.6	6.9	8.0	0.2	99.8			14.6
15.3		4.9	27.2	16.9	10.3	5.1	4.0	2.5	3.0	21.6	78.4			9.4
			12.4	7.7	8.4	11.5	10.0	10.3	9.7	7.7	92.3			22.3
19.9		8.2	36.5	8.7	4.6	2.6	2.8	2.2		32.1	67.9		10.5	
0.9		1.1	46.2	27.0	7.9	4.2	2.6			2.1	97.9	10.0		
1.6	14.9	18.7	55.5	2.1	0.5	0.7	0.8	1.2		35.8	64.2		3.4	

along range 907.6 to represent older deposits where there has been no overflow for many years.

Samples[5] collected for mineralogical study were obtained by thrusting a pipe, 2 inches in diameter, down into the sand of the river bed to a depth of about 40 inches, withdrawing it and removing the sand, which usually formed a core about 30 inches long, from inside the pipe. Five to ten such vertical cores were taken at equal distances on a line across the river channel at each of 19 sampling sites. Usually these were combined to form a

[5] These samples were collected principally by Gordon Rittenhouse and E. H. Moser, Jr.; analyses were by Dr. Rittenhouse and W. E. Bertholf, Jr.

composite sample and then split down to convenient size for laboratory study. Analyses have been made on two to five composite samples for each sampling site, collected at different times between 1937 and 1941, and these have been averaged to represent the texture of the river-bed sediment at these sites. Thin layers of silt or clay were occasionally removed from the cores to facilitate handling and mineral analysis, and where gravel or cobbles were encountered, in the upper part of the Valley, these were intentionally excluded by taking cores only down to the depth at which such coarser sediment was encountered.

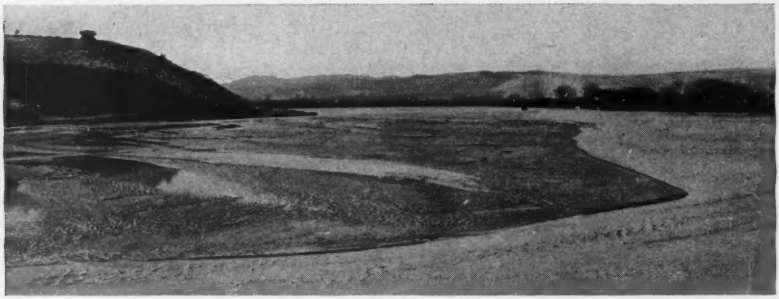

FIG. 2.—View down the Rio Grande from the San Acacia narrows. Sand bars in the river channel are typical of those from which the samples of highest density were collected, except that the river stage is somewhat higher than normal in this view, and the bars are thus more nearly covered.

AVERAGE TEXTURE OF SEDIMENT

The textural data on overbank deposits, as listed in table 1, have been applied to the average annual volumes of sediment accumulation computed from cross-section records for the period 1936–41, with results as shown in table 2. The general procedure was to average the textural data for pairs of successive samples and multiply these averages by the volume of annual accumulation computed for the segment bounded by ranges near the sampling sites. Textural samples were not collected on all range lines and not all sampling ranges coincide with boundaries of valley segments used for volume computations. Thus the coincidence between volume and textural data for some of the segments is not exact, but such deviations could not affect the totals to any significant degree. The wide spacing of cross-section ranges, and even wider spacing of samples, undoubtedly results in errors and non-significant variations in the data for individual segments, so that little critical significance can be attached to deviations in the computed texture from place to place. Such errors presumably are compensatory in nature, however, and the averages derived for the entire Valley, or for major parts of it, are believed to be reasonably representative.

In order to complete the data for 1936–41 deposits, similar volumetric computations for river-bed deposits were also made with results also summarized in table 2. This does not purport to be an accurate representation of all bed materials, however, but only a reasonable weighting of the available textural data as a step in deriving averages for all 1936–41 deposits. Although the cross sections show net aggradation for the river bed, it is impossible to determine just which parts of the bed deposits have accumulated within specific periods of

time because of the extensive shifting of such deposits during every major flood. Generally the textural samples represented the average composition of the upper few feet of the bed materials during the years 1937–40 rather than the 1936–41 deposits, but as previously noted, material coarser or finer than sand was commonly excluded in order to facilitate sand obviously forms fully 90% of the sediment sampled. Fortunately, the bed deposits comprise only about 11% of all 1936–41 deposits and, hence, the lesser accuracy of these data probably has little effect on the average sizes determined for the entire accumulation.

For convenient comparison, the texture of each major subdivision of the overbank

TABLE 2. *Summary of texture of Middle Rio Grande Valley sediment deposits, 1936–41*

Areal unit	Median grain size	Sand[1] >0.061 mm.		Silt 0.061–0.0039 mm.		Clay[2] <0.0039 mm.		Total
	Mm.	*Pct.*	*Ac.-ft./yr.*	*Pct.*	*Ac.-ft./yr.*	*Pct.*	*Ac.-ft./yr.*	*Ac.-ft./yr.*
Floodway, exclusive of river channel	0.034	29	886	46	1,411	25	764	3,061
Overflow areas outside floodway levees	0.042	34	649	51	968	15	294	1,911[3]
Floodplain below floodway levees	0.052	41	2,288	43	2,436	16	917	5,641[4]
All overbank floodplain deposits	0.047	36	3,823	45	4,815	19	1,975	10,613[3,4]
River bed deposits	0.163	98	1,293	2	28	—	—	1,321
All Conservancy District deposits	0.042	35	1,802	45	2,364	20	1,057	5,223[3]
All deposits below Conservancy District	0.060	49	3,314	37	2,479	14	917	6,690[4]
All Middle Rio Grande Valley deposits	0.054	43	5,116	41	4,843	16	1,974	11,933[3,4]

[1] All sediment coarser than 0.061 is included as sand, although a small part is actually coarser than sand size.
[2] All river bed sediment finer than 0.061 is included as silt, although a small part is probably of clay size.
[3] Exclusive of 79 acre-feet of deposits outside levees, for which there are no textural data.
[4] Exclusive of 57 acre-feet of deposits outside the main depositional area, chiefly derived from small lateral tributaries, for which there are no textural data.

the mineralogical studies. Above the mouth of Jemez Creek, or in about the upper 20 miles of the Valley, gravel is a major constituent of the bed material and more than half may be coarser than sand size. This is almost entirely unrepresented in the present data. There is no similar large proportion of finer sediment in any other part of the river deposits, but, in general, the exclusion of silty layers would tend to compensate for the coarser sizes excluded in the upper part of the Valley. Thus the median size, as determined by these methods, may not be seriously affected by such factors for

deposits and of the river-bed deposits has been shown in table 2 in terms of median grain size and also in terms of the sand, silt and clay size classification according to the Wentworth scale most commonly used for description of sediments. In terms of the soils classification used by the Department of Agriculture, the sand and clay content would each be somewhat higher and that of silt would be appreciably lower. These comparisons show the close similarity in the three groups of overbank deposits and the comparatively fine size of the river-bed sands. The overbank deposits in the Conserv-

ancy District floodway have a median size of about 0.034 mm., those in areas overflowed by levee breaks have a median of about 0.042 mm., and the median for the flood-plain deposits downstream from the Conservancy District levees is about 0.052 mm. All these medians fall in the coarsest silt size of the Wentworth classification, but the last is just above the lower limit of the very fine sand size of the soils classification. Silt is the dominant component of all groups according to the Wentworth classification, but according to the soils classification, silt and sand are nearly equal in two groups and sand is decidedly dominant below the floodway. For all the overbank deposits the median size is 0.047, which falls in the coarsest silt size of the Wentworth and the silt size of the soil classifications. The composition according to the Wentworth classes is 36 per cent sand, 45 per cent silt and 19 per cent clay. The figures become 46 per cent sand, 34 per cent silt and 20 per cent clay according to the soils classification.

The river-bed deposits are appreciably coarser than the overbank flood-plain deposits, the median size of 0.163 mm. computed for the river deposits being nearly four times the median for all overbank deposits, but fine and very fine sand are the dominant sizes even in the river-bed sediment. These two size grades form about 75 per cent of the total, according to the Wentworth classification, but this concentration of sizes is exaggerated because of the deliberate exclusion from the samples of much of the sediment coarser or finer than sand. There is a definite, although neither consistent nor uniform, downstream decrease in average size of the sand from Cochiti through the Valley to San Marcial, but the range in sand sizes is comparatively small. The range in average size of the bed materials is actually much greater than these data show, due to the large proportion of gravel above the mouth of Jemez Creek, as previously noted. Throughout most of the Valley the average size of the river-bed sand is also a little coarser than the median computed for the 1936–41 deposits, because the greater part of the latter are in the lower reaches where the average grain size is smallest.

For all the valley deposits accumulated from 1936 to 1941, the median grain size is approximately 0.054 mm. This is in the coarsest silt size of the Wentworth classification, or in the very fine sand size of the soil classification used by the Department of Agriculture. According to the Wentworth classification about 43% of the total sediment is sand, about 41% is silt, and about 16% is clay. The relative proportions according to the soils classification would be about 54% sand, 28% silt and 18% clay. Any errors involved in the river deposit data cannot affect these totals for all sediment to any considerable extent.

AVERAGE DENSITY OF SEDIMENTARY DEPOSITS

The samples collected for density determinations were chosen to represent both average and apparent extreme variations in texture and degree of compaction by drying, in major areas of deposition. This method of sampling was used because adequate systematic areal coverage would have involved more samples than could be handled in the limited time available. Textural analyses were also made on these, which are designated as "spot" samples in table 1, and the relations between density and median grain size are represented graphically in figure 3. No exact correlation between texture and density is to be expected, because of the differences in compaction dependent on extent of drying after exposure to the air, but, generally, there is an increase in density with increase in grain size. In the range of sizes representing the greater part of the deposits there appears to be sufficient uniformity to justify using the median grain size as the basis for estimating the average density of all deposits. For the median grain size of all Middle Valley 1936–41 deposits, determined as 0.054 mm. according to figure 4, the

average density is estimated to be approximately 86 pounds per cubic foot. This is essentially a weighted average of values of 85 pounds per cubic foot for all overbank deposits, and 100 pounds per cubic foot for all river-bed deposits. These values agree essentially with customary estimates and limited available data for similar deposits in other areas.

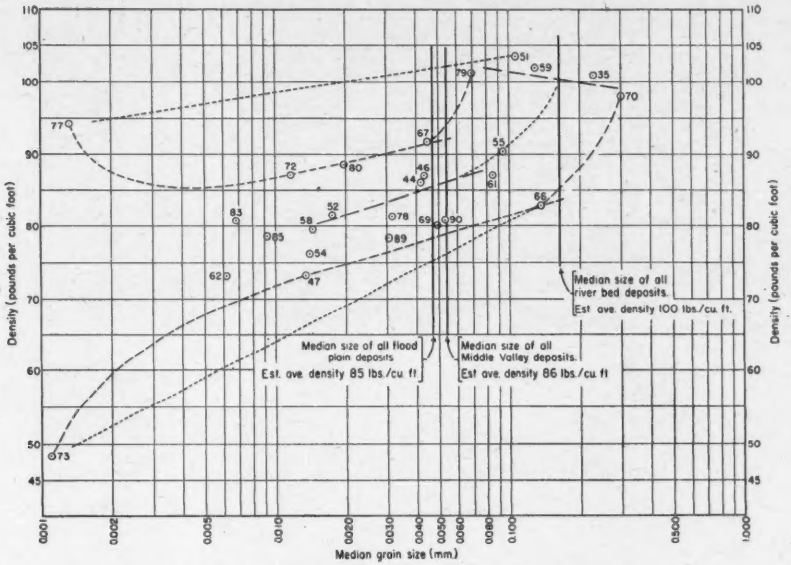
Density (pounds per cubic foot)
Median grain size (mm)
Median size of all river bed deposits.
Est ave. density 100 lbs./cu. ft.
Median size of all flood plain deposits
Est. ave. density 85 lbs./cu. ft.
Median size of all Middle Valley deposits.
Est ave. density 86 lbs./cu ft

FIG. 3.—Density and median grain size of Middle Rio Grande Valley sediment samples.

SIGNIFICANCE OF THE TEXTURAL DATA

Justification for Use of Sand as an Index of Sediment Sources

In connection with the other studies, an investigation of the mineralogical composition of the river-bed sands was carried on in an effort to determine the approximate relative contributions of sand from each of the major tributary areas. These studies were limited to the sand sizes by practical limitations of microscopic technique, but sand appeared to be the principal component of the sediment accumulating in the river channel. The extent to which the sand source estimates might apply to the entire volume of sediment was uncertain when the work was begun. Since the resurveys showed only about 11% of the 1936–41 sediment deposited in the river, there might be question as to the representative value of the sand-source data. The textural studies, however, show that the sand sizes used in the mineralogical studies constitute something like 40% of all 1936–41 deposits in the Middle Valley, and that the median size of all these deposits is only slightly smaller than the sand sizes studied. These relations justify use of the sand-source data as one of the best available guides to the sources of the sediment of all sizes, although there is no doubt that particular

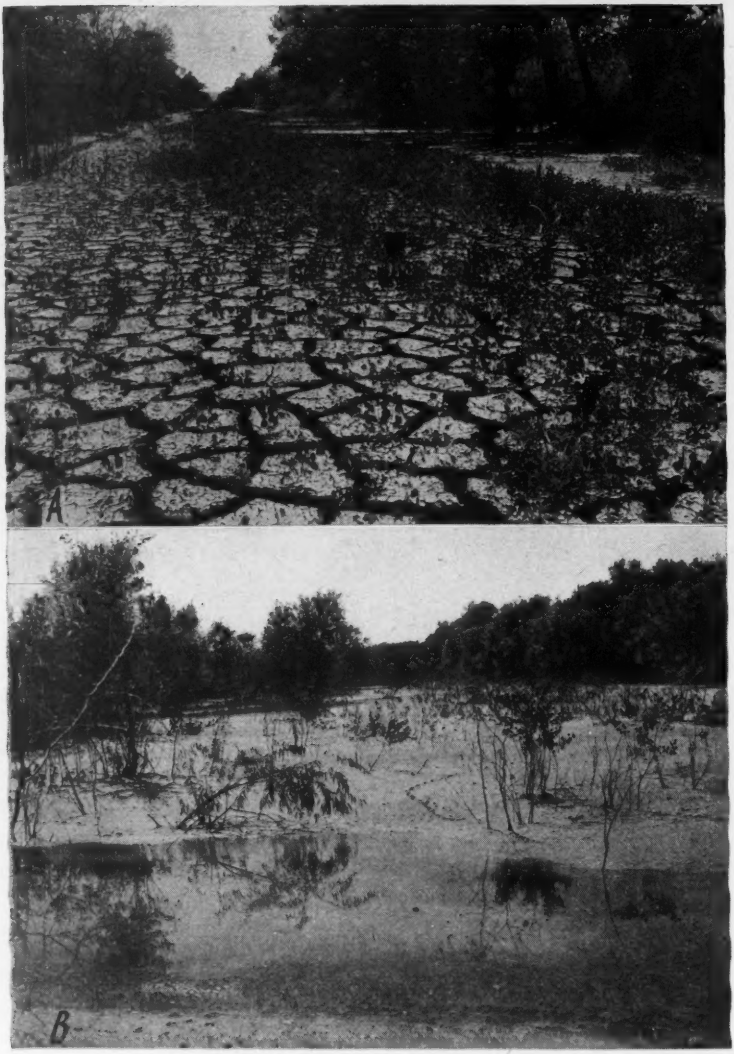

FIG. 4.—Environments typical of those in which the fine-grained sediments of highest and lowest density were collected. These pictures were taken within a few hundred feet of each other along the San Marcial-Val Verde road, in September, 1937. (A) Deeply sun-cracked and compacted deposits on the roadway; (B) soft, wet deposits in a shallow depression along an old, abandoned river channel.

tributaries may furnish a larger or smaller proportion of the coarser and finer sizes than they do of the sandy part of the sediment.

Sand Accumulation Due to Excessive Supply, Not Lag Accumulation

The textural data show a marked concentration of sand in the lower part of the Valley, below the floodway. This is due partly to the relatively large volume of river-bed deposits here, but the overbank deposits also are more sandy than those above. Several channel avulsions since 1936 undoubtedly have been a major factor in distributing sand out from the channel and over the flood plain in this area, but the sand could not have been concentrated here if the river were not capable of transporting it with comparative ease and rapidity. It follows that the sand deposits along the river channel must be caused chiefly by excessive volumes of delivery from tributaries, rather than by lag accumulation of sand too coarse for the stream to transport.

This is in accord with the small change in average size of the sand from the head of the valley to the lower end, but the gravel which is common in the upper 20 miles is an apparent exception. Particles of gravel size were frequently caught in a small sand trap operated for short periods during the waning stages of the large 1941 spring flood, and it is known that gravel is common in the bed deposits at depths within reach of the scouring action of major floods. Thus, it may be that gravel accumulation occurs generally throughout much of the Valley during major floods where only sand is visible in the surficial bed deposits. If this is the case, such gravel accumulation may actually be a major factor in the process of river aggradation. Present information on this point is inadequate for any evaluation or conclusions and it is a question that needs further investigation.

Importance of Avulsions and Splay Deposits in Fluvial Processes

The overbank deposits within the floodway are finer in median size and have a lower sand content than those deposited outside the levee breaks or in the lower section of the Valley. This is notable because the overbank floodway area is generally the natural levee area, which might be expected to have the coarsest part of the flood-plain sediment. The explanation appears to be that a larger proportion of the overbank sediment outside or below the levees consists of splay deposits (Happ, Rittenhouse and Dobson, 1940, p. 24), formed during periods of partial river avulsion. The splay deposits are composed essentially of bed sediment in contrast to the more widespread flood-plain deposits formed by settling of sediment carried in suspension. They usually have a relatively small areal extent but the present studies indicate that a river with a large sand burden, such as the Rio Grande, can form splays a mile or more in length and that these deposits can be a major factor in the aggradation of the flood plain. It follows that such processes deserve critical consideration in any studies of alluvial sedimentation, and that their relative importance in the flood-plain complex may provide a useful guide to interpretation of the dominant trends in sedimentary development. Present indications, based on the 1936–41 studies, are that channel avulsions and splay deposits are the dominant fluvial and sedimentary processes in the Middle Rio Grade Valley and that bank erosion and attendant lateral sediment accretion are of comparatively minor and local importance.

Texture as a Basis for Possible Evaluation of Erosional Processes

It is known that much of the Middle Valley sediment is being derived from widening, deepening, or headward extension of arroyo channels in lateral tributary

valleys. The banks of these intermittent and ephemeral stream channels are clearly exposed throughout the greater part of their lengths, and, in general, they show sandy silts and clays toward the top of the bank and sands or gravels below. Erosion of these arroyo banks is the principal source of the sand brought to the Rio Grande. Some sand is brought into the arroyos by wind action, but this is a minor factor. Surface sheet erosion, rill development and gullying on upland slopes contribute an unknown proportion of the total sediment, but furnish little sand or coarser material because of the selective deposition of such coarser sediment on colluvial slopes and alluvial fans. Adequate direct measurement of erosion rates on a drainage area of about 24,186 square miles, even on a sampling basis, would be a formidable task and can hardly be expected under any circumstances now predictable. Direct measurement of the rates of arroyo growth alone might be possible, but even this would be a great task and would require a considerable period of years to establish reasonable averages. The textural data, however, might be used as a basis for deriving an estimate that would be sufficiently reliable to have some value. This would require additional sampling of the deposits in Elephant Butte Reservoir and the arroyo bank material in order to obtain textural data for these materials similar to those now available for the Middle Valley deposits. It would be a large sampling and analytical program but not nearly so great as even very rough direct measurements of

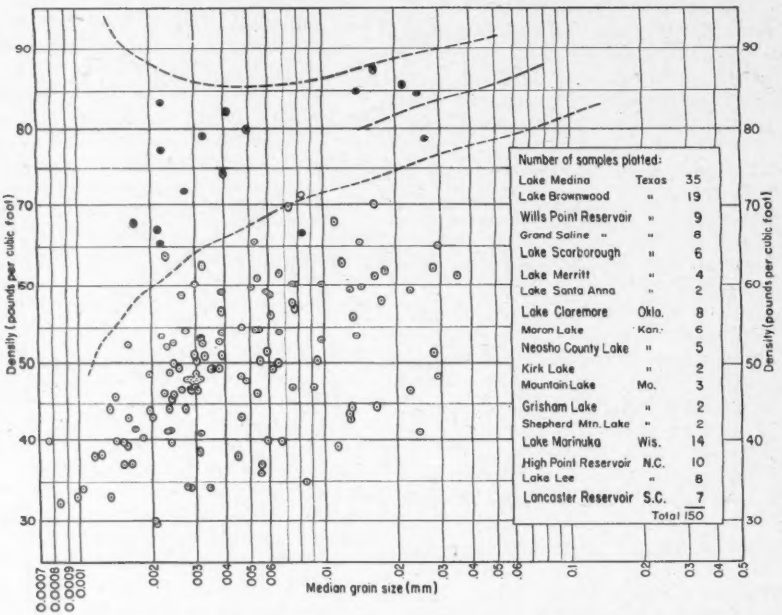
Density (pounds per cubic foot)
Median grain size (mm)
Number of samples plotted:
Lake Medina Texas 35
Lake Brownwood " 19
Wills Point Reservoir " 9
Grand Saline " " 8
Lake Scarborough " 6
Lake Merritt " 4
Lake Santa Anna " 2
Lake Claremore Okla. 8
Moran Lake Kan. 6
Neosho County Lake " 5
Kirk Lake " 2
Mountain Lake Mo. 3
Grisham Lake " 2
Shepherd Mtn. Lake " 2
Lake Marinuka Wis. 14
High Point Reservoir N.C. 10
Lake Lee " 8
Lancaster Reservoir S.C. 7
Total 150

FIG. 5.—Relation between median grain size and volume-weight ratio of sediments from artificial lakes. Samples indicated by a cross inside the circle are apparently similar to valley alluvial deposits. Dashed guide lines represent approximate limits and median for comparable Middle Rio Grande Valley deposits.

erosion rates throughout the entire drainage basin.

If the average texture of the valley and reservoir deposits proved to be very much like that of the arroyo banks, it could be assumed with reasonable assurance that contributions from sheet erosion and related processes other than arroyo growth are of negligible importance as sources of damaging sediment in the Valley or Reservoir. On the other hand, if the sedimentary deposits were found to contain a considerably larger proportion of fine sediment than the arroyo banks, the difference would provide a rough measure of the relative importance of the two principal processes of sediment production. Such a study might justify a considerable saving in any remedial program designed to alleviate the sedimentation problems by erosion-retarding methods.

SIGNIFICANCE OF THE DENSITY DATA

Median Grain Size as a Basis for Average Density Estimates

The samples for density studies were selected to represent the average condition of the 1936–41 deposits, as they were at the time of the 1941 resurveys. In places there had been some drying and, hence, probably compaction, between the time of survey and the time of sampling, but in general this change had not been of significant magnitude. There were also places where further drying and compaction probably continued after the sampling so that the volume of the deposits would become somewhat less and their density somewhat greater than is indicated by present data, but such changes of important magnitude probably would not affect any large proportion of the sediment. Most of the sediment had already been subject to air drying for periods of 3 to 6 months at the time of sampling.

There can be no doubt that air drying is the major factor in determining the apparent density, at least of the finer sediments, in such an environment. Samples 73 and 77, which are very similar in texture, illustrate this point. The former was collected from a site which had been exposed only a day or so previously by draining off of overflow water, and only an inch or so above the level at which water was still standing in shallow pools a few feet away. It is close to the lower limit of density which could be measured by the collecting method used. Sample 77, in contrast, was from a deeply cracked, obviously thoroughly air-dried sample which had been exposed by subsidence of the flood waters at least 4 months prior to the sampling. This had practically twice the density of sample 73. The spread between the outer guide lines, as drawn on figure 2, probably represents the approximate magnitude of the factor of compaction by drying for the Middle Valley samples.

The median grain size was chosen as the basis for applying the density data to all deposits, after comparison with trial plottings of density against percentages of sand, silt, and clay, respectively. All these other methods of plotting showed about the same range of variation as that for median grain size, with the sand percentage giving slightly less variation than the other two, but none of them provided as close control as did the median size plotting, in the size range corresponding to the average texture of all deposits. The average density estimated for all deposits would have been about 89 pounds per cubic foot if based on the sand content, about 88 if based on silt content, and about 82 if based on the clay and colloid content, but these values would have been taken from parts of the curves obviously poorly defined by the available data. Comparison has also been made with a curve for density plotted against sand content, prepared by Lane and Koelzer (1942, figure 2), to represent reservoir deposits but including a large proportion of samples representative of alluvial sediment. From this curve, the average density of the Middle Valley deposits would be estimated as 85 pounds per cubic foot, rather than 86,

as derived by the methods used for this report. This slight difference suggests that there is little difference in the reliability of the methods for such textures, but the median size method has the advantage of being applicable also to sediments in which the sand content is too small to be diagnostic.

The inner pair of the limiting guide lines from figure 3 are also shown on figure 4, which is a plotting of density against median grain size for 150 samples of sediment from 18 reservoirs or artificial lakes studied by the Soil Conservation Service. The sampling methods used for the reservoir sediment were different, and there is greater uncertainty concerning the accuracy of volumes of samples collected under water, but at least 16 of these reservoir samples were from deposits either above the water level at time of sampling, or which had been exposed to air drying for considerable periods at some time. All but one of these 16 samples fall within the inner guide lines drawn from the Middle Valley data and the other is not far outside. This suggests that the data may have considerable value for application to other alluvial deposits and to those lacustrine deposits which are subject to similar conditions of exposure and compaction. Obviously they are not applicable to lacustrine deposits not so exposed, except possibly as an indication of the density such sediments might attain after a very long period of compaction. Some of the other reservoir samples probably are also comparable to those from the Middle Valley, which might indicate a greater scattering of points in figure 3, but information has not been adequate to make definite decisions on all samples. The reservoir samples also support the curves drawn from the Middle Valley data, because they include a number of samples in the size range for which there were comparatively few Middle Valley samples.

The state of flocculation of the finer particles will be an important factor in comparison of these texture-density relations with those of other alluvial deposits. In general, calcium content is high in the Rio Grande sediments and many samples of suspended-load sediment have been found to be highly flocculated. On the other hand, some of the fine-textured alluvial soils in areas of poor drainage have been reported to be highly dispersed because of the influence of black alkali, or sodium carbonate (Poulsen and Fitzpatrick, 1929, p. 22). The samples used in the present investigation were all dispersed by addition of small quantities of a peptizing agent and agitation prior to mechanical analysis and the state of flocculation under natural conditions was not particularly investigated. Field inspection suggested that all the samples probably were well flocculated, but this may be in error, and variations of the degree of flocculation may account for part of the spread in the plotted data. In figure 3, sample 77 provides the only basis for drawing the upper limiting curve to show an increase in density with decreasing grain size in the clay range. In the field samples 77 and 80 appeared to represent the same type of sediment, stage of drying, and general environment, and their difference in weight appears to be a good illustration of the greater density of clay than silt, but if the material of sample 77 was much more highly flocculated its effective grain size may have been considerably coarser than is indicated by the analysis after dispersion.

CORRELATION WITH RATES OF SOIL EROSION

The principal purpose of the textural and density studies was to provide a basis for correlating the volumes of sedimentation in the Middle Valley and Elephant Butte Reservoir with rates of erosion in the contributing drainage basin. This objective cannot be fully attained until more complete data are also available concerning the other factors in the problem, but some general approximations can be made from present data.

For the upland soils and alluvial deposits subject to erosion in tributary

valleys, the average density is probably not appreciably different from the 86 pounds per cubic foot estimated for the Middle Valley deposits. There are no adequate data on the upland soils of the Middle Rio Grande drainage area, but in other regions alluvial soils are usually similar in density to the upland soils of the same drainage basin. At Mexican Springs, near Gallup in the Colorado River drainage basin but not far west of the Rio Grande area, measurements on eight soil series, as reported by Free, Browning and Musgrave (1940, table 5), showed an average volume-weight ratio of 84 pounds per cubic foot. These soils are generally similar to soils of a large part of the Middle Rio Grande drainage area and occur in a similar environment. In the upper part of the Gila River basin, in southeastern Arizona and southwestern New Mexico, Fletcher and Beutner (1941, table 4) determined the volume-weight ratios for four soil series which average 96 pounds per cubic foot in an undisturbed condition, but these were all gravelly soils and hence would probably be heavier than the average for the Rio Grande area. The latter includes considerable areas of gravelly soils, but gravel is not of significant volume in the 1936–41 Middle Valley deposits, and it is unlikely these deposits would be equivalent in weight to gravelly soils. Hence, for present practical purposes, it is assumed that the 12,000 acre-feet per year of average Middle Valley accumulation is approximately equivalent to erosion of 12,000 acre-feet of soil and tributary-valley alluvium.

Present data are not adequate for a direct comparison between volumes of sedimentation in the Middle Valley and in Elephant Butte Reservoir, but during the period October 1, 1936 to October 1, 1941 the total suspended load of the Rio Grande at San Marcial was 47,583,342 tons as reported by the International Boundary Commission (Water Bulletins, 1936–1941, inclusive). This corresponds approximately to the period between the 1936 and 1941 valley surveys. Practically all of the suspended load passing San Marcial was carried into the Reservoir, the total 1936–41 deposition between the gaging station and Range A, at the head of the Reservoir, amounting to only about 166 acre-feet or an average of 34 acre-feet per year. If the suspended load going into the Reservoir from the Middle Valley had an average density of 86 pounds per cubic foot in place, prior to its erosion, it would be equivalent to an average of 5,045 acre-feet per year for the period 1936–41. Added to about 12,069 acre-feet per year accumulated in the Middle Valley, this would indicate a net erosion of about 17,100 acre-feet per year. For the total drainage area of 24,186 square miles, this would be equivalent to 2.07 tons per acre or 0.7 acre-feet per square mile per year. Allowance for bed-load movement past the San Marcial station, which may not be adequately represented in the suspended-load figures, and for minor alluvial fans and irrigation ditch and field deposits in the Valley, might raise these estimates somewhat, but whether the difference would be of significant magnitude is not known. Probably at least 90% of the total sediment output was derived from grazing lands in New Mexico aggregating less than half the total drainage area. For these areas the sediment output rate might be twice as great as the average for the entire basin.

Prior to 1936 the rate of sedimentation in Elephant Butte Reservoir had been considerably higher than is suggested by the suspended-load record for the years 1936–41. Present rather scanty data suggest that the rate of river aggradation in the Middle Valley has not changed greatly since about 1918, or for a period comparable to the life of the reservoir, but it is doubtful whether or not the volumetric rate of sedimentation in the Valley has been equally high all this time. Several channel avulsions in the vicinity of San Marcial are known to have caused extensive local flood-plain sedimentation in the period 1936–41, which undoubtedly increased the rate of the

Valley deposition and correspondingly decreased the proportion carried into the reservoir. There are at least two lines of evidence by which some estimate of the magnitude of this effect can be made.

During the period 1926–36 the average rate of sedimentation was about 975 acre-feet per year between ranges 1000(J) and 1006.8(A). This is approximately the lower half of the 14-mile reach in which the avulsions occurred, and in the period 1936–41 the average rate here was about 2,644 acre-feet per year. If this same proportion was maintained throughout the entire lower 14 miles of the Valley, the increase would amount to 63% of the 1936–41 average rate.

Another approximation can be made from the San Marcial suspended-load records. The average annual suspended load, for the period 1925–36, inclusive, prior to the avulsions, averaged about 17,600,000 tons per year, compared to only about 9,500,000 tons per year for the period 1937–41 (Water Bulletins 6–11, inclusive). The difference, if deposited in the Valley with an average density of 86 pounds per cubic foot, would amount to about 4,300 acre-feet, or 64% of the 1936–41 average in the lower 14 miles of the Valley.

The close similarity of these figures, 63% and 64%, is undoubtedly fortuitous. Other higher figures could be obtained by other methods of handling the data. The average discharge was considerably higher in the latter period, for instance, and a higher figure might be justified by consideration of this factor if there were adequate basis for selecting such a higher value. It seems safely conservative, therefore, to estimate in round figures that about 60% of the 1936–41 deposits in the lower 14 miles of the Valley, or about 4,000 acre-feet per year, represent the increased deposition due to channel avulsions in this reach. This would still leave something like 8,000 acre-feet per year as the "normal" rate of Middle Valley accumulation, for comparison with longer-period rates of reservoir accumulation. The average rate of reservoir sedimentation was about 18,000 acre-feet per year from 1914 to 1935, according to computations by the Bureau of Reclamation from the 1935 cooperative survey (Eakin, 1939, p. 92). If allowance be made for about 11,004 acre-feet of sediment deposited above crest elevation on the delta, about 3,432 acre-feet in the dead storage area, and an estimated 5,000 acre-feet passing through the reservoir as density flows (Fiock, 1934), the total annual rate would approximate 19,000 acre-feet per year. This may be in excess by an amount corresponding to the sediment accumulation in the reservoir area between the time of the original surveys, from 1903 to 1908, and the beginning of reservoir storage in January 1915.

The average density of the Elephant Butte deposits is not known with any accuracy, but some approximations can be made. For the period 1925–35 the International Boundary Commission derived a figure of 70.1 pounds per cubic foot, based on records of reservoir surveys in 1925 and 1935 and suspended-load measurements at San Marcial during the intervening period (1937, p. 63). Unfortunately, the 1925 survey did not cover the entire reservoir, and hence, the accuracy of the figure used for volume of sediment is subject to considerable doubt. For the period 1914–35 the Soil Conservation Service, using a similar method but somewhat different data, computed an average density of 52 pounds per cubic foot.[6] This was based in part on estimates of suspended load taken from rating curves[7] and applied to the discharge for 8 years during which samples were not taken. Both these figures would be reduced if allowance were made for sediment carried out of the reservoir by density currents

[6] Compiled by L. M. Glymph, Jr., for Department of Agriculture Report on Survey for Runoff and Water Flow Retardation and Soil Erosion Prevention on the Watershed of the Rio Puerco, 1941 (mimeographed; subject to revision). See p. 325.

[7] Compiled by T. R. Neiswander, of the Rio Grande Project, Bureau of Reclamation, from records of sampling for the years 1905–12 and 1919.

and for sediment accumulated in the original dead storage area. The figure of 70.1 pounds would be further reduced if allowance were made for sediment deposited above the crest elevation in the delta area below the gaging station, and for compaction, during the period 1925–35, of sediment previously deposited. On the other hand, both figures would be raised if allowance were made for sediment carried past San Marcial as bed load and not adequately represented in the suspended-load records and for sediment brought into the reservoir by direct tributaries below the gaging station. The figure of 52 pounds would be raised further if there had been any sediment accumulation in the reservoir area between the time of the original topographic surveys, from 1903 to 1908, and the beginning of reservoir operation in January 1915. From consideration of plausible magnitudes for these unknown factors it seems that the true average density may be somewhere between the two estimates.

If the average density of the reservoir deposits is somewhere between 52 and 70.1 pounds per cubic foot, an accumulation of about 19,000 acre-feet per year would be equivalent to erosion of between 15,500 and 11,500 acre-feet of upland soil or valley alluvium averaging 86 pounds per cubic foot. Added to about 8,000 acre-feet of "normal" Middle Valley accumulation, this would indicate an average rate of sediment output, or net erosion, of between 19,500 and 23,500 acre feet per year for the contributing drainage basin. These estimates are approximately 15% and 38% higher than the estimate of 17,000 acre-feet for the period 1936–41. Thus it appears that the rates of sedimentation measured for the period 1936–41 are more probably below than above the rates which may be expected to prevail over a longer period.

REFERENCES

CURRY, ALBERT S., *1931*, A comparison of methods for determining the volume-weight of soils: *Jour. Agricultural Research*, vol. 42, pp. 765–772.

EAKIN, HENRY M., *1939*, Silting of reservoirs: *U. S. Dept. Agr.* Tech. Bull. 524. 142 pp. (rev. by Carl B. Brown).

FIOCK, L. R., *1934*, Records of silt carried by the Rio Grande and its accumulation in Elephant Butte Reservoir: *Amer. Geophys. Union Trans.* Ann. Meeting 15 (pt. 2), pp. 468–473.

FLETCHER, JOEL E., and BEUTNER, E. L., *1941*, Erodibility investigations on some soils of the upper Gila watershed: *U. S. Dept. Agr.* Tech. Bull. 794, 31 pp.

FREE, G. R., BROWNING, G. M., and MUSGRAVE, G. W., *1940*, Relative infiltration and related physical characteristics of certain soils: *U. S. Dept. Agr.* Tech. Bull. 729, 51 pp.

HAPP, STAFFORD C., RITTENHOUSE, GORDON, and DOBSON, G. C., *1940*, Some principles of accelerated stream and valley sedimentation: *U. S. Dept. Agr.* Tech. Bull. 695, 134 pp.

INTERNATIONAL BOUNDARY COMMISSION, UNITED STATES AND MEXICO, *1936–41*, Water Bulletins 6–11, inclusive.

LANE, E. W., and KOELZER, VICTOR, *1942*, The density of sediments deposited in reservoirs: *St. Paul Engineer District Sub-Office*, Hydraulic Laboratory, University of Iowa, Iowa City, Iowa, 51 pp., duplicated (preliminary edition, subject to revision).

POULSEN, E. N., and FITZPATRICK, E. G., *1929*, Soil survey of the Socorro and Rio Puerco areas, New Mexico: *U. S. Bur. Chem. and Soils.*

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 14, NO. 1, PP. 20–25
FIG. 1, TABLES 1–2, APRIL, 1944

ERRORS OF SAMPLING SANDS FOR MECHANICAL ANALYSIS

GORDON RITTENHOUSE AND MARK P. CONNAUGHTON
Soil Conservation Service, Greenville, South Carolina, and Washington, D. C.

ABSTRACT

The errors involved in determining the median grain size, the Trask sorting coefficient, and the percentages of sediment in individual size grades are presented for fluvial sands and for heavy minerals in such sands. The relation between sampling errors for heavy minerals and for entire samples is discussed.

During the past few years the relation of soil erosion and arroyo trenching to channel aggradation and other forms of injurious sedimentation in the Middle Rio Grande Valley, N. M., has been under investigation by the Soil Conservation Service. As part of this comprehensive investigation, the senior writer determined the relative importance of various sediment sources.[1] Samples of channel sands that were collected for this study have yielded information on the errors involved in sampling and analyzing fine sands. The junior writer has obtained similar data on coarse sands from the Enoree River, near Taylors, S. C., where the Soil Conservation Service maintained a sediment-load laboratory.

This paper presents these data and, by showing the errors to which individual size grades are subject, extends the previous work of Krumbein (1934), McKelvey (1940), and Walker (1941). Also included are error data for heavy minerals, and a brief discussion of some relations between sampling errors for heavy minerals and for entire samples.

In general, the approach and techniques followed were those outlined by Krumbein (1941). Briefly summarized, Krumbein's reasoning was as follows: If a series of closely spaced samples are collected and analyzed, the variations between them will represent all errors, E, to which they are subject. If a composite is prepared, and various splits from it are analyzed individually, the variation between the splits will include all laboratory errors, e_2. The field error, e_1, may then be determined from the equation

$$e_1 = \sqrt{E^2 - e_2^2}$$

This field error includes both the variation inherent in sampling a statistically homogeneous deposit, and the variation due to the characteristic lack of homogeneity of sedimentary deposits. Although these two sub-errors are independent, they cannot be separately evaluated. Krumbein expressed his results as probable errors, i.e., the error that will not be exceeded in one half of the observed cases. The writers have expressed their results as coefficients of variation,[2] C, and have changed Krumbein's data to this basis. This was done to eliminate the size factor in comparing results from different localities.

All Rio Grande sampling localities were on reaches of the channel. At each locality, the samples were collected at six to eight evenly spaced intervals across the high-water channel by forcing a 2-inch diameter pipe about 40 inches into the channel deposits. Sediment cores so obtained ranged from 23 to 34 inches in

[1] Rittenhouse, Gordon, "The heavy mineral method for evaluation of sediment sources," submitted for publication as a U. S. Dept. Agric. Technical Bulletin. Manuscript in the files of the Sedimentation Section, Soil Conservation Service. Rittenhouse, Gordon, "Sources of modern sand in the Middle Rio Grande Valley, N. M.," *Jour. Geol.* In Press.

[2] The coefficient of variation is the standard deviation divided by the arithmetic mean. It also equals 1.4825 times the probable error divided by the arithmetic mean. The coefficient of variation will not be exceeded in 68 out of 100 cases.

length. In the few places that the surface sand was dry, part of the sample was collected from the side of a hole dug to water level, and part as a core. Thin silt or clay layers that overlay or were interbedded with the channel sands were eliminated at the time of collection.

For the Enoree River, samples were spaced as shown in figure 1. At each sampling point, a pipe nipple, 4 inches long and $1\frac{1}{4}$ inches in diameter, was forced slightly more than its own length into the channel bed. In order that data on weight per unit volume could also be obtained, care was taken to fill the nipple completely and to disturb the sediment as little as possible.

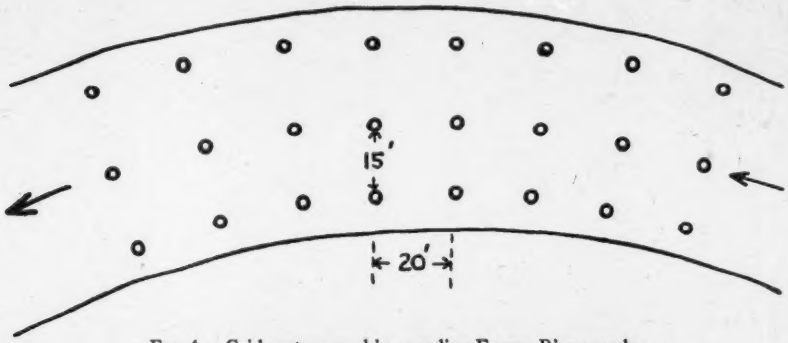

FIG. 1.—Grid system used in sampling Enoree River sands.

In the laboratory the samples were dried, split to about 100 grams, and placed in a nest of sieves in which the size of openings increased progressively from fine to coarse approximately as the $\sqrt{2}$. After 14 minutes sieving in a Rotap mechanical shaker, the sand collected on each sieve was weighed and the percentage by weight retained on each sieve was calculated. The cumulative size-distribution curves were plotted and the median and Trask sorting coefficient (Trask, 1932) obtained. Coefficients of variation (*C*) were calculated for each size grade, for the median, and for the Trask sorting coefficient.

The total laboratory error was determined from composite samples that were made by combining proportional splits from all six RG 8, 1938 (Albuquerque), samples and from all twenty-four Enoree River samples. After thorough mixing, eight splits were made from each composite, the splits were separately analyzed, and the coefficients of variation were computed. The field errors were then calculated. These error data, together with Krumbein's Waverly Beach, Ind., data are presented in table 1.

Size distributions by weight were determined for twelve heavy minerals in the RG 12, 1940 (Bosque), samples by a method described elsewhere (Rittenhouse, 1943). The total errors for heavy minerals are presented in table 2. Laboratory errors have not been determined but, as will be shown, they are believed to be relatively small. If so, the total coefficient of variation and the field coefficient of variation for heavy minerals would be about the same.

For the median grain sizes of Rio Grande and Enoree River sands (table 1), the total errors (and presumably the field errors) are somewhat larger than those determined by Krumbein. This may be due in part to greater distance between samples at each collecting locality but more likely is due to the greater

TABLE 1.—*Coefficient of variation of sampling sands for mechanical analysis*

Location, mean, and coefficient of variation (*C*)	Samples	Size Grade													Derived values			
		>3.962 mm.	3.962 to 1.981 mm.	1.981 to 1.397 mm.	1.397 to .991 mm.	.991 to .701 mm.	.701 to .495 mm.	.495 to .351 mm.	.351 to .250 mm.	.250 to .175 mm.	.175 to .124 mm.	<.124 mm.	.124 to .088 mm.	.088 to .061 mm.	<.061 mm.	*Md*		*So*[3]	
	Number	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Mm.*	*Pct.*		*Pct.*
RG 8, 1938 (Albuquerque, N.M.)																			
Mean	6	—	—	—	1.1	1.0	3.5	9.1	22.1	20.3	21.4	—	12.3	3.8	5.3	0.193	—	1.47	—
Total *C*	6	—	—	—	61.	50.	31.	15.	19.	13.	21.	—	20.	19.	56.	—	6.8	—	4.8
Field *C*	6	—	—	—	60.	49.	31.	15.	19.	13.	21.	—	20.	19.	56.	—	6.7	—	4.8
Laboratory *C*	8	—	—	—	11.	7.9	2.2	2.3	2.1	2.3	2.0	—	2.3	2.0	4.4	—	1.2	—	0.7
RG 8, 1940 (Albuquerque, N.M.)																			
Mean	8	—	—	—	2.4	1.7	4.2	8.6	18.9	26.2	23.5	—	10.7	2.4	1.7	0.207	—	1.43	—
Total *C*	8	—	—	—	82.	86.	43.	24.	19.	12.	17.	—	15.	15.	34.	—	8.8	—	5.9
RG 9, 1940 (Isleta, N.M.)																			
Mean	8	—	—	—	1.6	1.0	2.7	6.6	17.7	24.9	23.6	—	13.8	4.3	3.8	0.192	—	1.37	—
Total *C*	8	—	—	—	82.	55.	44.	41.	40.	23.	26.	—	50.	76.	111.	—	20.	—	3.6
RG 10, 1940 (Los Lunas, N.M.)																			
Mean	7	—	—	—	0.9	1.0	3.7	8.5	18.7	25.9	25.8	—	12.3	2.2	1.0	0.205	—	1.39	—
Total *C*	7	—	—	—	95.	92.	79.	53.	16.	20.	22.	—	31.	31.	42.	—	16.	—	4.5
RG 11, 1940 (Belin, N.M.)																			
Mean	7	—	—	—	0.8	0.9	3.1	7.5	18.5	26.0	22.9	—	14.8	3.6	1.9	0.197	—	1.40	—
Total *C*	7	—	—	—	60.	67.	57.	48.	34.	18.	22.	—	54.	59.	87.	—	18.	—	3.7
RG 12, 1940 (Bosque, N.M.)																			
Mean	8	—	—	—	1.3	1.1	3.2	7.1	17.6	27.5	24.6	—	12.4	3.1	2.1	0.198	—	1.37	—
Total *C*	8	—	—	—	69.	69.	46.	39.	30.	9.2	26.	—	26.	34.	77.	—	12.	—	4.2
Mean[1]	6	—	—	—	1.1	1.0	3.0	6.8	17.3	27.6	25.4	—	12.6	3.0	2.0	0.197	—	1.37	—
Total *C*[1]	6	—	—	—	82.	76.	53.	44.	35.	10.	27.	—	30.	41.	88.	—	13.	—	4.5
Enoree River, S.C.																			
Mean	24	2.5	18.5	19.4	25.9	19.8	9.0	2.8	0.6	0.4	0.4	0.6	—	—	—	1.233	—	1.44	—
Total *C*	24	53.	20.	14.	13.	17.	24.	44.	78.	68.	88.	74.	—	—	—	—	7.3	—	5.2
Field *C*	24	46.	19.	13.	13.	16.	24.	43.	77.	66.	86.	70.	—	—	—	—	6.9	—	5 0
Laboratory *C*	8	27.	6.0	4.6	2.1	4.3	6.8	9.5	9.7	18.	18.	24.	—	—	—	—	2.4	—	1.4
Waverly Beach, Ind.[2]																			
Mean	24	—	—	—	—	0.3	2.0	11.4	45.7	32.8	7.3	—	0.2	—	—	0.264	—	—	—
Total *C*	24	—	—	—	—	100.	85.	47.	9.6	25.	37.	—	128.	—	—	—	6.8	—	—
Field *C*	24	—	—	—	—	97.	85.	47.	9.0	24.	32.	—	126.	—	—	—	6.8	—	—
Laboratory *C*	8	—	—	—	—	26.	6.	1.8	3.5	7.2	19.	—	22.	—	—	—	0.8	—	—

[1] For samples from which heavy mineral data in table 2 were obtained.
[2] Krumbein, *op. cit.*; data recomputed from probable error to coefficient of variation base.
[3] Trask sorting coefficient.

TABLE 2.—*Coefficients of variation for selected heavy minerals in Rio Grande samples collected at RG 12 (Bosque) in 1940*

Mineral		Size grade							Derived values			
		.495–.351 mm.	.351–.246 mm.	.246–.175 mm.	.175–.124 mm.	.124–.088 mm.	.088–.061 mm.	.061 mm.	Median		Sorting	
		Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Mm.*	*Pct.*		*Pct.*
Magnetite	Mean	0.8	2.7	8.2	20.7	36.6	20.6	10.2	0.107	—	1.27	—
	C	47.	36.	54.	51.	11.	45.	46.	—	15.	—	2.9
Ilmenite	Mean	0.1	1.2	5.9	17.6	37.1	22.5	15.7	0.100	—	1.28	—
	C	—	76.	87.	61.	11.	38.	48.	—	15.	—	5.1
Pyroxene	Mean	1.8	8.5	19.4	31.8	25.7	8.7	3.9	0.142	—	1.32	—
	C	51.	70.	24.	12.	28.	34.	31.	—	13.	—	3.8
Hypersthene	Mean	0.8	4.1	22.2	29.7	26.8	10.6	5.6	0.138	—	1.31	—
	C	130.	55.	58.	13.	49.	50.	42.	—	15.	—	4.9
Blue-green hornblende	Mean	0.9	5.5	18.1	35.9	29.3	7.3	3.1	0.130	—	1.27	—
	C	95.	63.	44.	17.	23.	26.	51.	—	13.	—	4.7
Green hornblende	Mean	0.4	3.9	15.7	28.9	32.5	12.7	5.9	0.126	—	1.32	—
	C	140.	106.	48.	19.	24.	35.	68.	—	12.	—	5.2
Brown hornblende	Mean	0.7	1.7	9.3	32.1	34.4	15.0	6.7	0.120	—	1.27	—
	C	123.	180.	44.	26.	31.	15.	77.	—	12.	—	4.7
Tourmaline	Mean	0.1	1.8	5.3	27.4	37.2	19.7	8.3	0.109	—	1.26	—
	C	—	65.0	59.	41.	14.	33.	40.	—	10.	—	4.5
Zircon	Mean	—	0.3	0.6	6.5	20.5	32.7	39.3	0.071	—	—	—
	C	—	—	—	88.	40.	26.	18.	—	16.	—	—
Apatite	Mean	0.1	3.2	6.5	21.6	35.7	19.9	12.2	0.107	—	1.29	—
	C	—	87.	94.	32.	35.	27.	27.	—	16.	—	5.2
Garnet	Mean	1.4	5.7	11.1	25.4	36.1	15.1	6.7	0.122	—	1.23	—
	C	98.	100.	98.	46.	47.	61.	68.	—	18.	—	6.5
Titanite	Mean	0.7	3.5	11.1	31.2	34.5	13.0	6.0	0.122	—	1.29	—
	C	—	113.	60.	23.	14.	45.	99.	—	11.	—	3.5

range of hydraulic conditions at each collecting locality. The laboratory errors are also somewhat larger than Krumbein's, but like his, are so much smaller than the field errors that they are a negligible part of the total error. Errors in the Trask sorting coefficient are smaller than those for median grain size. The laboratory errors of the sorting coefficient are much smaller than the field errors.

The total C, the field C, and the laboratory C vary greatly from size grade to size grade within each sample. In general, the errors for individual size grades appear to be inversely proportional to the square of the percentage of the sample in the size grades. There is a tendency, however, for the total and field errors to be larger in the better sorted samples. There is also evidence that the errors are larger for coarse size grades than for fine size grades that contain the same percentage of sand. Except for the modal grade, the total and field errors for individual size grades are much larger than the total and field errors for the median grain size and the sorting coefficient.

For heavy minerals (table 2), the total errors of the medians and sorting coefficients are about the same as those for the entire samples from the same collecting locality. This contrasts with the findings of Krumbein and Rassmussen (1941), who found that the sampling error for heavy minerals was more than twice as large as that for mean grain size. They recognized, however, that their heavy mineral and entire sample errors were not entirely comparable.

For entire samples, the total error and field errors are much larger than the laboratory errors. If the total errors for heavy minerals and entire samples are essentially the same, the field error for heavies either must be (1) much larger than the laboratory error, or (2) much smaller than the field error for the entire samples. To determine which of these two possibilities is most probable, consideration must be given to the dynamics of sediment accumulation.

At any place in a stream cross section, the hydraulic conditions that govern sediment deposition will vary with time. The size distribution in the deposit reflects the net effect of these temporal fluctuations. At other places in the cross section, similar fluctuations will occur, but their intensities will not be the same. Consequently, the size distribution of sediment in different parts of the cross section will vary. Almost all of the field error for entire samples will ordinarily be due to such differences. The heavy minerals in each part of a deposit must have been deposited under the same range of hydraulic conditions, whatever they may have been, as the lighter minerals with which they are associated. Therefore, their size distributions may be expected to vary from place to place in the cross section to about the same extent as do the size distributions of the entire samples in which they occur. If this is true, the field error for heavies is large relative to the laboratory error.

For individual size grades of heavy minerals, the total errors decrease as the percentage of sample in the size grades increases. In this respect, the heavy minerals and the entire samples are similar. Because the heavy minerals are finer textured than the entire samples, however, the lowest errors for the heavies occur in finer size grades than do those for the entire samples. In general, the shift is greater for heavies of high density (magnetite, ilmenite, zircon) than for heavies of low density (hornblendes, pyroxene, apatite). Thus, for some size grades the heavy mineral errors would be larger and for some size grades they would be smaller than the errors for entire samples.

These conclusions have been based on the comparison of size distributions by weight. If the more commonly used number percentage method of representing heavy mineral compositions had been used instead, very different results would have been obtained. The errors involved in using number percentages and other methods of representing heavy mineral compositions have been discussed else-

where by the senior writer (Rittenhouse, 1943).

Some data were also obtained on the relative importance of various laboratory operations. For the median grain size of the Enoree sands, the total laboratory error of 2.4 per cent is composed of a splitting error of 1.9 per cent, a sieving error of 1.4 per cent, and a plotting error of .5 per cent. For the Trask sorting coefficient, the total laboratory error of 1.4 per cent is composed of a splitting error of 1.3 per cent and a combined sieving and plotting error of .6 per cent. Measurable wear of the grains occurred during repeated sieving of the same sample, being noticeable as a loss in the two coarsest grades and an accretion in the finer size grades and the pan. This has increased the sieving error and decreased the splitting error slightly.

Data on the variations in weight per unit volume were obtained from the Enoree River samples. The mean weight per unit volume was 90 pounds per cubic foot and the total coefficient of variation was 5.2 per cent.

ACKNOWLEDGMENTS

The writers wish to thank C. B. Brown and N. L. Stoltenberg for their criticism of the manuscript.

REFERENCES

KRUMBEIN, W. C., *1941*, The probable error of sampling sediments for mechanical analysis: *Amer. Jour. Sci.*, vol. 27, pp. 204–214.

KRUMBEIN, W. C., and RASMUSSEN, W. C., *1941*, The probable error of sampling beach sand for heavy mineral analysis: *Jour. Sed. Pet.*, vol. 11, pp. 10–20.

MCKELVEY, V. E., *1940*, Beach Sediments of Trout Lake, Wisconsin: *Jour. Sed. Pet.*, vol. 10, pp. 65–77.

RITTENHOUSE, GORDON, *1943*. Transportation and deposition of heavy minerals: *Geol. Soc. Amer. Bull.*, vol. 54, pp. 1725–1780.

TRASK, PARKER, *1932*, Origin and environment of source sediments of petroleum: Houston, p. 71.

WALKER, STANTON, *1941*, Reproducibility of tests of foundry sand: *A. F. A. Trans.*, vol. 49, pp. 1–31.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 14, NO. 1, PP. 26–28
PLATE I, APRIL, 1944

BEACH MARKINGS MADE BY SAND HOPPERS

K. O. EMERY
Scripps Institution of Oceanography, La Jolla, California
Contributions from the Scripps Institution of Oceanography, New Series, No. 220

ABSTRACT

Beach markings made by sand hoppers are very common on some California beaches. These have characteristics which may permit their recognition in ancient sands with consequent identification of the sand as a former marine beach deposit.

INTRODUCTION

The writer has observed characteristic beach markings made by sand hoppers, or sand fleas, on a number of beaches in California. The markings are especially well developed near San Diego where most of the beach sand consists of laminae of light colored quartz and feldspar alternating with laminae of dark colored heavy minerals, similar to California beach sands described by Thompson (1937). In some places at the upper part of the beach these materials form alternating layers several centimeters in thickness.

The beaches support an abundant population of sand hoppers, a type of amphipod which feeds largely on kelp washed ashore by the waves. During the day, the hoppers either conceal themselves under kelp, or hide in ready-made holes formed by wave action (Palmer, 1928), or dig their own burrows (Bryson, 1865; Reid, 1938; Schellenberg, 1928; Verwey, 1929). Where they make burrows, characteristic patterns are formed by the sand which is removed during excavation. These patterns are abundant only on beaches of fine to medium sand and have not been observed by the writer on beaches of very coarse sand. They occur chiefly on the upper part of the beach near the high tide mark.

DESCRIPTION OF MARKINGS

One marking found on all beaches examined resembles a small ant hill. It is made by one or more species of small hopper which makes a burrow about 2 mm. in diameter and 1 to 2 cm. deep. The sand which is removed forms a small mound about 2 cm. in diameter and 5 mm. high but not very distinctive.

Much more striking are markings formed by a larger hopper which reaches a length of 3 cm. There are several species of these large hoppers but *Orchestoidea californiana* is by far most common near San Diego. A number of specimens were kindly identified by Dr. Martin Johnson. This hopper, on digging a hole, throws the sand backwards with powerful kicks until the hole is about 1 cm. deep, then it turns and kicks sand out of the hole in a direction approximately 180° opposite from that in which the first sand was thrown. By repeated turning and throwing out of sand, the hopper forms two rays of sand, each of which may have a length of 10 to 25 cm. and a width of 3 to 6 cm. The hole is elliptical and 5 to 12 mm. in longest diameter. The depth is commonly 10 to 25 cm. Another hopper, *Talitrus saltator*, makes the same kind of marking (Schellenberg, 1928).

Where the beach consists of alternating light and dark colored layers, the sand encountered near the bottom of the burrow may have a different color from that at the surface, so that the rays very often consist of dark sand lying upon a light colored sand surface. Such rays are very apparent even to casual observers (Pl. I, fig. 1). Usually a number of burrows occur within a small area so that rays from adjacent burrows intersect, giving rise to a "chicken-track" sort of pattern (Pl. I, fig. 2).

Burrowing starts immediately after the tide has uncovered the beach, but the best rays are formed several hours later

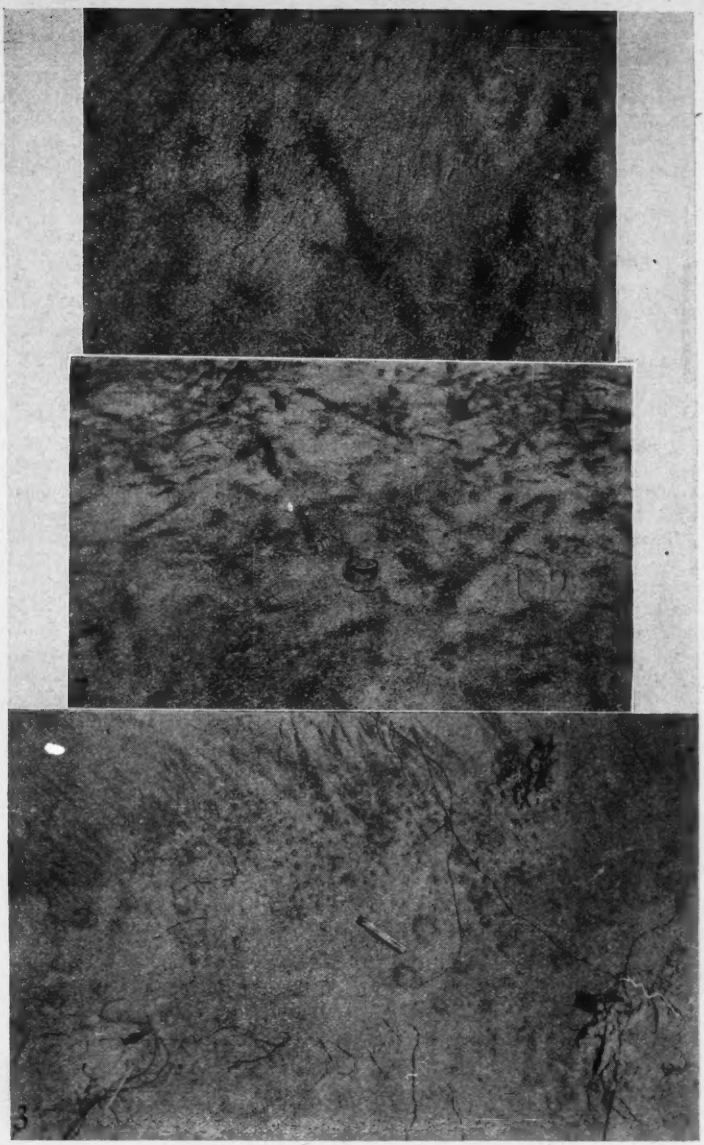

PLATE I

FIG. 1.—Ray pattern made by sand hoppers. Dark colored heavy mineral sand thrown from the burrows lies on light colored quartz and feldspar sand. The area covered by the photograph is about 1.5 × 1.0 meters.

FIG. 2.—"Chicken-track" pattern developed by intersecting rays from many sand hopper burrows. Scale is given by heel print in foreground.

FIG. 3.—Truncated bases of sand domes formed above sand hopper burrows. Note that these are concentric rings of dark and light colored sand and not domes projecting above the general surface of the beach.

when the sand is dry enough so that the grains do not stick together in lumps. Exposure of the markings for periods of several days usually results in obliteration or burial of the markings by rays from newer burrows. As the tide again covers the beach, the markings are destroyed except possibly under favorable conditions which may allow their burial just as rain prints, tracks, and swash marks are preserved (Fairchild, 1901; Clarke, 1918).

SAND DOMES

As high tide approaches, the incoming waves wash higher and higher on the beach. Usually the rays are destroyed by the first few waves which cover them. These waves or others following them very often form sand domes over the tops of the burrows. The domes are initiated by a wave which covers the top of the burrow with a plug of wet sand. As the next wave washes over the beach, water percolates into the sides of the burrow, displacing the air of the hole. Because the cover of wet sand over the hole is more or less air-tight, the air becomes slightly compressed. The pressure is released either by blowing out part of the cover of sand or by lifting up a dome of sand, and forming an "air laccolith." Domes formed in this manner commonly range from 1 to 12 cm. in diameter, and 2 to 30 mm. high with a roof thickness of 2 to 30 mm. The next wave which washes over the dome usually destroys it, but by truncating it so that the upturned edges are bevelled. Where the dome roof consists of several alternating laminae of light and dark colored sand, the site of the dome is marked by concentric rings of alternating light and dark sand. Many such rings can be seen near the upper part of the beach reached by the tide (Pl. I, fig. 3). Other domes examined by the writer were formed over small holes made by expulsion of interstitial air of the sand by an advancing wave as described by Palmer (1928). Domes have been described elsewhere as the result of still different processes (Reade, 1884).

GEOLOGICAL SIGNIFICANCE

Sand hoppers belong to the suborder Gammaridea which includes the family Talitridae of which at least two genera are known to form the ray-type beach marking. The geological age of this family is unknown, but closely related amphipods have been reported present in Tertiary and possibly also in Silurian rocks (Zittel, 1885). Therefore, markings similar to those formed at the present time may be present in ancient sediments. Such markings should be supplementary indications of a marine beach environment because they require a temporary drying of the beach such as occurs between tides.

The sand domes which form above a burrow are probably ephemeral but their truncated bases could be preserved in ancient water laid sands. However, neither the domes nor their bases may be diagnostic of marine beach conditions for they may be formed by more than one process.

REFERENCES

Bryson, A., *1865*, Surface markings on sandstone: *Geol. Mag.*, vol. 2, pp. 189–191.

Clarke, J. M., *1918*, Strand and undertow markings of upper Devonian time as indications of the prevailing climate: *N. Y. State Mus. Bull.*, vol. 196, pp. 199–239.

Fairchild, H. L., *1901*, Beach structure in Medina sandstone: *Am. Geol.*, vol. 28, pp. 9–14.

Palmer, R. H., *1928*, Sand holes of the strand: *Jour. of Geol.*, vol. 36, pp. 176–180.

Reade, T. M., *1884*, Miniature domes in sand: *Geol. Mag.*, vol. 21, pp. 20–22.

Reid, D. M., *1938*, Burrowing methods of *Talorchestia deshayesii* (Audouin) (Crustacea, Amphipoda): *Ann. & Mag. of Nat. Hist.*, series XI, vol. 1, pp. 155–157.

Schellenberg, Von A., *1928*, Beobachtungen an dem Amphipoden *Talitrus saltator* (Mont.): *Zoologischer Anzeiger*, vol. 79, pp. 78–82.

Thompson, W. O., *1937*, Original structures of beaches, bars, and dunes: *Bull. Geol. Soc. Am.*, vol. 48, pp. 723–752.

Verwey, J., *1929*, Einiges aus der Biologie von *Talitrus saltator* (Mont.): *Congrès Internation Xe Zool. à Budapest*, pt. 2, pp. 1156–1162.

Zittel, Karl, *1885*, *Handbuch der Palaeontologie*, vol. II, pp. 670–674.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 14, NO. 1, PP. 29–38
TABLES 1–8, APRIL, 1944

PETROLOGY OF THE PENNSYLVANIAN CYCLES OF THE SAINT LOUIS AREA

ALBERT J. FRANK
St. Louis University, St. Louis, Missouri

ABSTRACT

The minerals occurring in each division of a Pennsylvanian cyclothem at St. Louis, Missouri, have been determined and have yielded information about their sources and conditions of deposition. The climate was warm and moist both in the area of deposition and in the area, Ozarkia, from which the sediments were derived. At the beginning of the Pennsylvanian, the land was elevated as a whole and laterization took place forming a regolith composed of chert and sometimes sand at the top, ranging down through halloysite and kaolinite clay, through kaolinite clay and chert to illite clay and chert and sand, or to limestones containing them. The land rose in the upland regions giving rise to overloaded streams and the formation of alluvial plains and lagoons in which the materials of the above laterized regolith were laid down, topmost formation first. The land was sinking slowly and about the time the illite was reached, swamp conditions had come into being with the accumulation of decaying vegetation from which coal was to form. Subsidence quickened and the sea invaded the continent. However, the sea at first was shallow and conditions were good for the formation of pyrite. Meanwhile the illite, or rock containing illite, was being eroded and as the sea became deeper, conditions for the formation of pyrite became less favorable and shales containing illite and limestones were formed. The land began to rise and finally the sea left the land. Laterization again took place and the process was repeated.

INTRODUCTION

In 1930 J. M. Weller pointed out that the Pennsylvanian is composed of repetitions of certain sequences of sediments. "In detail the typical Pennsylvanian formation is composed of the following members:

Marine	8. Shale, containing "ironstone" bands in upper part and thin limestone layers in lower part
	7. Limestone
	6. Calcareous shale
	5. Black "fissile" shale
Continental	4. Coal
	3. Underclays, not uncommonly containing concretionary or bedded freshwater limestone
	2. Sandy and micaceous shale
	1. Sandstone
	Unconformity

The succession of beds at any particular locality may be incomplete." Such a recurrent series of beds was later called a "cyclothem" by Wanless and Weller.

The present study was undertaken to determine the mineral composition of most of the members of a typical cyclothem; to observe the relationship of kind and quantity of minerals to each part or member of the cycle; to find if any minerals present give clews to climatic conditions, source of sediments, conditions of transportation, and deposition.

ACKNOWLEDGMENTS

The author is deeply indebted to Victor T. Allen without whose help and direction this study could not have been accomplished. The writer is also indebted to Ross R. Heinrich who accompanied the writer on some of the field trips. Finally, the author thanks the Missouri Portland Cement Company and the Hydraulic Press Brick Company for access to their pits and for the courtesy shown him during this investigation.

STRATIGRAPHY

The Cherokee formation of the Penn-

sylvanian outlier at St. Louis, Missouri, was chosen for the study. This is the area to which Knight in 1933 applied the idea of cyclothems, subdividing it on the basis of the cycles, lettering them A, B, C, etc., from the lowest to the highest. This study includes the members of cycle A and the first member of cycle B as exposed at the Prospect Hill Pit of the Missouri Portland Cement Company, Riverview Drive (locality 1—in the northern portion of the outlier) and the members of cycles A and B as exposed at the Hydraulic Press Brick Company Pit, Ballas and Ladue Roads (locality 2—in the southwestern portion of the outlier). Before continuing with an examination of the beds as exposed it is well to render that discussion as clear as possible by considering the method of numbering adopted in this paper.

The method of numbering used is such as to convey the locality, cycle, member of cycle, and bed or zone in each member when a member was found to consist of differently appearing beds. The cycles are represented by capital letters exactly after Knight (p. 32) and the members are numbered after Weller. The beds are divided by using small letters. In all of these, the order used is ascending. An example will render the numbering clear:

Number "1	B	1	b"
Designates locality; i.e., 1 (Prospect Hill).	Designates the cycle; i.e., the 2nd cycle at the locality given by the proceeding number.	Designates the member of the cycle; i.e., in this case, member 1 of cycle B.	Designates the bed or zone; i.e., "b," the 2nd bed or zone in the member, in this case, member 1.

We can now briefly consider the section.

1A3

The lowest bed at Prospect Hill is the Cheltenham fireclay. This clay is a very light gray in color and has nodules in its lower portion.

2A3

At the Hydraulic Press Brick Company pit the Cheltenham is very similar to the Cheltenham at locality 1; however, the clay is much whiter in color.

1A4

Above the Cheltenham at locality 1 is a layer of coal, sometimes identified as the Bevier, between a foot and one-half and two feet thick. A hard, pyritiferous grit replaces the coal at the south end of the pit; this grit appeared to be about one foot thick.

2A4

The coal at locality 2 is about 18 inches thick.

1A5

A black fissile shale overlies the coal at Prospect Hill. It is less than three feet thick.

2A5

The black fissile shale is absent at locality 2; in its place is a thin bedded light gray non-calcareous shale which is three feet thick.

1A8

Member 8 at Prospect Hill is divided into three main divisions. The lower one, a massive gray shale merging into a tan shale in places, is about 35 feet thick. Next is a red shale about 25 feet thick. The topmost member is a red-brown shale whose maximum thickness is about 10 feet. The total thickness of 1A8 is about 70 feet.

The massive gray shale, $1A8a_1$ grades upward at the western edge of the pit into a tan shale, $1A8a_3$. There is a transition zone, $1A8a_2$, showing that the tan shale is merely the gray shale leached of its color; this was accomplished by ground water as the gray shale is leached or oxidized to tan along joints. At the eastern part of the pit the massive gray shale changes very little and sample $1A8a_4$ which was taken just below the contact with the overlying red shale, is a tannish-gray phase of the gray shale.

The red shale, 1A8b, overlies 1A8a and

varies little in the entire exposure.

The uppermost division of member 8 is a reddish-brown shale, 1A8c. This member is variable in thickness.

2A8

Member 8 at the Hydraulic pit can be divided into three main parts which are thought roughly to correspond with the three main divisions of member 8 at Prospect Hill.

The lowest zone is a massive gray shale, $2A8a_1$ and overlying this is a tan shale, $2A8a_2$. Their combined thickness is about 15 feet.

Over 10 feet of the reddish-tan shale, 2A8b were noted. This shale is thought to correspond to the red shale 1A8b.

The brownish-red shale, 2A8c, seems to be at least 10 feet thick.

Uncomformity

The uncomformity is very obscure at the Hydraulic pit; at Prospect Hill, however, this erosional uncomformity can be seen.

1B1

At Prospect Hill the bed overlying the red-brown shale is a gray, sandy shale or shaly sandstone, 1B1a. The next bed above is a yellow or brownish sandstone, 1B1b, which is heavy bedded and quite hard. 1B1 is about 10 feet thick. This forms the topmost bed at Prospect Hill. It is overlain by loess.

2B1

2B1 is heavy bedded soft sandstone. It is about five feet thick.

2B2

Member 2 of cycle B can be seen at the Hydraulic pit. It consists of clay or shale which weathers into small angular pieces, gray within, but coated on the outside with purple. It is about three feet thick.

2B3

The last bed studied in this investigation is a rather pure fireclay, light gray to white in color and about six inches thick.

RESULTS

In this investigation, the ordinary sedimentation methods of petrographical investigation were used. The study was divided into clay mineral studies, heavy mineral studies, light mineral studies, and thin section studies.

1A3 was not studied, as Allen has pointed out that the clay mineral of 1A3 is kaolinite.

1B1b is kaolinite for kaolinite has an index (gamma) of 1.566. The kaolinite also can be seen in thin section.

The other members all have been determined to be illite from their indices which, except in the case of 1A5, agree perfectly with those of illite as initially described by Grim, Bray and Bradley. The index of 1A5 is high compared with the indices of the other clays but the authors in the aforementioned paper describe illite with a gamma of 1.605; moreover 1A5 in thin section has the appearance of sericite-like illite. Therefore, the clay has been determined to be illite. Perhaps its slightly higher index is due to a high ferric iron content.

Clay Minerals

TABLE 1 (Prospect Hill)

Number	Index	(Between)	Remarks	Mineral
1B1b	1.565	1.570		Kaolinite
1B1a	1.580	1.590	Biaxial negative, par. ext.	Illite
1A8c	1.580	1.590	Biaxial negative	Illite
1A8b	1.580	1.590	Seems to be negative	Illite
$1A8a_4$	1.580	1.590		Illite
$1A8a_3$	1.580	1.590		Illite
$1A8a_2$	1.580	1.590		Illite
$1A8a_1$	1.580	1.590	Seems to be negative	Illite
1A5	1.590	1.601	Very near 1.590	Illite
1A3			Taken from Allen	Kaolinite

TABLE 2 (Hydraulic Press Brick Company Pit)

Number	Index	(Between)	Remarks	Mineral
2B3	1.560	1.565		Kaolinite (some halloysite)
2B2	1.560	1.565		Kaolinite (some halloysite)
2B1	1.580	1.590		Illite
2A8c	1.580	1.590	Seems to be negative	Illite
2A8b	1.580	1.590		Illite
2A8a_1	1.570	1.575		Illite and kaolinite
2A5	1.575	1.580		Illite and kaolinite
2A3	1.565	1.570		Kaolinite

Heavy Minerals

TABLE 3 (Prospect Hill)

	1A5	1A8a_1	1A8a_3	1A8a_4	1A8b	1A8c	1B1a	1B1b
Zircon	5	15	19	5	10	16	18	48
Tourmaline	3	13	21	2	5	6	14	13
Chlorite		13	11	20	18	6	23	
Barite			6	<1	4	6	11	16
Titanite	1	10	16	1	3	7	4	6
Rutile		<1		T	<1	<1	1	5
Ilmenite	2	7	3	8	14	31	10	<1
Magnetite	4	11	11	15	14	21	12	1
Pyrite	76	8	8	20	14	<1	<1	1
Limonite	6	14	1	18	6	2	2	1
Hematite	2	8	1	10	10	2	3	5
Leucoxene	1	1		1	2	1	1	2
Apatite					T			
Hornblende			3			1	T	
Garnet					<1			T
Anatase				T				1

(In the above table: < = less than, T = Trace)

TABLE 4 (Hydraulic Press Brick Company Pit)

	2A3	2A5	2A8a_1	2A8b	2A8c	2B1	2B2	2B3
Zircon	56	1	5	5	8	9	6	17
Tourmaline	15	<1	4	3	15	7	7	17
Chlorite				6	9			
Barite					1			
Titanite	14	<1	<1	<1	5	1	2	7
Rutile	4			<1		1	1	2
Ilmenite	4	<1	3	<1	7		9	3
Magnetite	4	<1	2	6	8	1	51	10
Pyrite	2	98	77	4	26			1
Limonite			3	72	8	76	9	7
Hematite			5		7	4	11	32
Leucoxene			<1	3	5	1	3	3
Apatite					<1			<1
Garnet	T				T		<1	T
Chalcopyrite			<1		<1			

(In the above table < = less than, T = trace)

TABLE 5 (Prospect Hill)

	1A5	1A8a$_1$	1A8a$_3$	1A8a$_4$	1A8b	1A8c	1B1a	1B1b
Quartz	85	70	65	55	70	70	83	92
Orthoclase		7	15	5	6	7	3	1
Albite			10	12	15	18	5	
Andesine	3	15		20			3	1
Micro-perthite				T				
Calcite							<1	
Gypsum							<1	
Phlogopite		1	2	1	3	2		<1
Muscovite		1	2	2	2	1	1	<1
Biotite		<1	1	T		1	2	1
Sericite	2	3	4	2	2	1	1	2
Organic matter	10	2	1	2	2		1	2

(In tables 5 and 6: < = less than, T = trace)

The clay of 2A3 is kaolinite which has a gamma of 1.566. The index of 2A5 lies between 1.575 and 1.580; this fact coupled with thin section study shows that this clay is made up of kaolinite and illite. The clay of 2A8a$_1$ is kaolinite in great part with some illite.

In 2A8a$_2$ the illite has increased until it is in the majority while kaolinite is subordinate. This is shown in thin section.

By the time 2A8b was being laid down, the clay mineral was entirely illite; 2A8c and 2B1 are also illite.

Clays 2B2 and 2B3 are mostly kaolinite. Although gamma of kaolinite is 1.566, there is some variation and therefore, the clay might be kaolinite with a lower index. What is much more likely, the clay "mineral" is a mixture made up mostly of kaolinite with small amounts of halloysite. X-ray studies are needed to verify this.

While the results given in the two preceding tables are as accurate as possible, the real purpose of indicating percentages in the tables is to show the approximate relationship of the quantities of different minerals present. The tables serve to indicate what minerals are present.

Light Minerals

The results obtained from the light-mineral study, while useful in showing what minerals are present, do not have as high a degree of accuracy as desirable in so far as the percentages are concerned.

In tables 3, 4, 5, and 6, a trace was recorded when only one grain of a mineral was seen in a sample.

TABLE 6 (Hydraulic Press Brick Company Pit)

	2A3	2A5	2A8a$_1$	2A8b	2A8c	2B1	2B2	2B3
Quartz	95	85	85	85	79	80	93	75
Orthoclase			5	4	8	6	2	
Albite				4				
Andesine	2	1			4	5		
Calcite					1			20
Gypsum							T	
Phlogopite				2	1	1	1	
Muscovite				1	1	1	1	
Biotite								3
Sericite		8	5	2	3	2		
Organic matter	3	6	5	2	3	5	2	2

TABLE 7.—*Weights of lights and heavies at Prospect Hill*

Number	Gm. of Lights	Gm. of Heavies
$1A8a_1$	8.19	0.19
$1A8a_3$	12.44	0.04
$1A8a_4$	9.06	0.04
1A8b	16.22	0.06
1A8c	10.46	0.09
1B1a	49.27	0.20
1B1b	32.18	0.42

Chemical Data

No X-ray or chemical studies were carried on during the present investigation. While chemical composition can be approximated from the results obtained in the mineral studies, chemical analyses of some members appear in the literature.

CONCLUSIONS

V. T. Allen has proposed a theory for the origin of the Cheltenham underclay. The data of this study substantiate the theory and justify its extension. In brief, Allen's theory is as follows:

"A generalized section of the weathered surface developed on the older rocks at the beginning of Pennsylvanian time, in keeping with the information available, follows:

IV. Chert—concentrated at surface.

III. Halloysite—kaolinite clay and chert.

II. Kaolinite clay and layers of weathered chert retaining somewhat their parallelism of bedding.

TABLE 8.—*Weights of lights and heavies at the hydraulic pit*

Number	Gm. of Lights	Gm. of Heavies
2A3	6.15	0.06
2A5	0.02	4.54
$2A8a_1$	0.125	0.008
2A8b	3.515	0.43
2A8c	1.50	0.08
2B1	8.06	1.43
2B2	7.06	1.24
2B3	14.20	1.11

I. Grades downward into Mississippian cherty limestone and Ozarkian, Canadian, and Ordovician cherty dolomitic limestones containing clay composed of the sericite-like mineral [illite] or beidellite."

"When erosion of the weathered material took place, deposition followed in the reverse order of the arrangement of the material in the weathered zones" (p. 26). This is shown to have taken place in Allen's section:

"Blue and gray clays—composed of sericite-like mineral [illite], kaolinite, quartz.

Green clays—composed of sericite-like mineral [illite], pyrite, kaolinite, quartz.

Disconformity.....

Cheltenham

(3) Plastic or semi-plastic clay composed of kaolinite, quartz, and little sericite-like mineral [illite].

(2) Flint clay—composed of halloysite and kaolinite.

(1) Conglomerate or sandstone—composed of quartz and chert" (p. 24).

Let us now consider cyclothem A and part of B in the light of Allen's theory, the results of the present study, and other known facts.

The results of the mineral studies are outstanding in their relationship to Allen's theory for by the extension of the theory to an entire cyclothem (and therefore to all cyclothems of a Pennsylvanian section) all the data are adqeuately explained.

The clay of 1A3 (Table 1) is kaolinite. As we go up in the section we reach 1A5 whose clay is illite. The clay mineral remains illite for the remainder of cycle A.

Cycle B is clearly explained by a reapplication of Allen's idea. Another period of kaolinization or laterization was followed by more deposition in the reverse order of the arrangement of the material in the weathered zones.

The relationship of the results to the theory is even clearer at locality 2 for here we have (Table 2, cycle A) kaolinite

merging to kaolinite and illite (see explanation of Table 2), then to illite and kaolinite and finally to illite.

The members of cycle B lying above A at locality 2 clearly testify to the advisability of a reapplication of Allen's theory. Kaolinization took place and the weathered chert at the top of the new regolith was deposited as 2B1; then the kaolinite with some halloysite was reached by weathering and deposited as 2B2 and 2B3.

Just as the clay mineral studies help us understand the weathering in place and subsequent denudation of the regolith the heavy mineral studies help us understand where that land mass was situated or where the sediments came from.

The heavy mineral studies confirm the fact that these Pennsylvanian formations could well have come from the Ordovician. Studies of the heavy mineral content of the Jefferson City and Cotter sandstones (both lower Ordovician) have been carried on by Grawe and Cullison. By comparing tables 3 and 4 with their results it can be seen that there is almost complete agreement between the allogenic minerals found by them and those found during the present investigation. The mineral which prevents complete agreement is rutile which was not noted by Grawe and Cullison. However, any allogenic rutile present may have been masked by the sphalerite which was one of the authigenic minerals present in their samples.

Studies of the St. Peter sandstone (Ordovician) by Thiel show that the same heavy minerals are present in this sandstone as are present in the Pennsylvanian. For one example Thiel gives: zircon 21%, tourmaline 36%, rutile 20%, leucoxene 23%.

Becker found the same minerals for the upper Cambrian in Wisconsin. The beds he studied are equivalent to the Ozarkian and conceivably the Ozarkian has the same heavy minerals as the lower Pennsylvanian and some of the Pennsylvanian could have been derived from the Ozarkian.

It is thought that some of the material came from the Warsaw (Mississippian). In the absence of concrete evidence that the Warsaw has the same heavy mineral assemblage as the Pennsylvanian one might suppose that some of the Warsaw came from reworked Ordovician or even from the upper Cambrian. This Warsaw was then reworked to form cycle A in accordance with the idea that the uppermost formations of the Mississippian are responsible for much of the lower Pennsylvanian. However it must be mentioned that these ideas are slightly mitigated against by the medium-rounded appearance of many of the heavy minerals which do not appear to have undergone very much transportation or reworking.

It is well to consider the land masses of Pennsylvanian time, all of which are possible source areas of the sediments. Ozarkia occupied over one-fourth of Missouri and parts of Illinois and Arkansas. Llanoria was situated southwest of Ozarkia. To the east lay Applachia. The Canadian land mass toward the north had a southwestern, peninsula-like extension. While the author believes that the seas between these land masses were connected, the results of the present study, arguing for an Ozarkia source, could be used to argue for disconnected seas.

The majority of writers think that the northern land area with its western extension contributed only a small, if any, quantity of sediment. A fact, in the present investigation pointing against this northern land mass as a source area, is that there is only a trace of garnet in the cyclothem studied (Tables 3 and 4) while many, though not all, of the possible source rocks in the northern land area contain garnet. Probably some of the more northern Pennsylvanian deposits contain material from this northern land mass. Yet the evidence is apparently strong enough to eliminate the northern mass as a source of any large quantity of Pennsylvanian sediment in Missouri.

There are grave doubts as to whether any of the material of the cyclothems

studied in this investigation came from Appalachia. Appalachia is a region of metamorphic rocks; these contain such minerals as kyanite, epidote, and garnet. Kyanite and epidote are absent and there is only a trace of garnet in the sediments studied during the present investigation (Tables 3 and 4). Either the kyanite belt was not uncovered or the sediments did not come from Appalachia.

There is some question as to whether Ozarkia was a land mass in Pennsylvanian times. Nevertheless nearly all the authors admit that Ozarkia was a land mass during the early Pennsylvanian. If Ozarkia was above the sea, the sediments coming from Llanoria would have been blocked by Ozarkia and at least in the area studied there should be no sediment from Llanoria.

Accordingly, Ozarkia is the only land mass from which the majority of sediment could have been derived. In fact, Ozarkia probably even contributed fairly much to the Illinois lower Pennsylvanian for the Cincinnati arch, though below water, probably had the effect of cutting of some of the sediment from Appalachia.

As mentioned before, the Warsaw and other sediments are considered as contributors to the Pennsylvanian. Yet the question may arise as to whether the igneous areas of the Ozarks contributed any sediments. This possibility is remote for Tolman and Koch found 3% of epidote and traces of garnet in the Graniteville granite and small quantities of epidote and traces of garnet in the Silver Mine granite.

It must not be forgotten that while Ozarkia was the contributor to the area studied, the other land masses, especially Appalachia and Llanoria, contributed very much to the Pennsylvanian in other areas.

The light mineral studies confirm the idea of kaolinization. Feldspars are absent or scarce in those members derived from the kaolinized portion of the regolith (Tables 5 and 6). In the heavy mineral studies rutile serves the same purpose. It is present in relative abundance in the members from the kaolinized portion of the regolith but is present only in small amounts in the members from the unkaolinized regolith. It is thought that the rutile is both allogenic and authigenic in the kaolinized portion of the regolith for the rutile as viewed in the continental members seemed to be of two kinds, rounded and only slightly worn well-formed crystals. In the members from the lower or non-kaolin part of the regolith the rutile is thought to be allogenic.

It might be possible to tell if one is in the continental or marine portion of a cyclothem by the relative abundance or absence of rutile, feldspar, and chlorite (Tables 3, 4, 5, 6). If this study was extended to include many localities and many cycles it might also be possible to correlate by using mineral content as shown in the tables.

As previously stated, the Pennsylvanian cyclothem consists of continental members at the base and marine members at the top. The close of the Mississippian, a period of marine sedimentation, was followed by regional uplift. Laterization took place on this plain forming kaolin. The area was flat and gently slopping and the streams were sluggish. Ozarkia, Appalachia, and other land areas were uplifted further and the streams which had been eroding the plains became overloaded and their sediments were deposited upon the plains where erosion by the streams had already taken place.

In the St. Louis area the cherts, formed at the surface in Ozarkia before its uplift, were deposited first; these deposited cherts were seen at locality 2. This chert came from division IV of Allen's section.

As erosion began to cut into the laterized regolith, division III was reached. Division III of the St. Louis source area was either thin or the streams were not yet overloaded enough to drop the fine halloysite and it was carried seaward, for very little halloysite was deposited in the Cheltenham of the St. Louis area. Finally division II was reached by erosion and the kaolinite and weathered chert were

eroded and deposited by the aggrading streams on the alluvial plains as the Cheltenham.

Thus the chert at the bottom of cyclothem A and member 3 of A were laid down.

The plains had been stationary and with the deposition of member 3 the streams were aggraded, deposition ceased and some erosion took place. Then the land began to slowly sink and swamp conditions came into being, and a luxuriant jungle vegetation, which had existed on the laterized portion, sprang up on the plains. In the swamps thus formed, member A4, the coal was deposited both from plant growth in place and from incoming material. The subsidence of the land quickened and the sea invaded the continent, the shoreline of Ozarkia being very near St. Louis. Members 1A5 and 2A5 were deposited in the new sea; 2A5 probably preceded 1A5 for 2A5 has much kaolinite derived from division II of the regolith while 1A5 is illite derived from division I. Another possibility is that the portion of the regolith supplying the clay minerals to the Prospect Hill members had eroded quicker or initially had been less thick in division II than the portion of the regolith supplying the clay minerals at the Hydraulic pit (Tables 1 and 2).

Of these times we can make further suppositions based on the heavy mineral study. The heavy minerals of the layer, 2A5, above the coal at the Hydraulic pit, show a veritable "flood" of pyrite (Table 4). Also in this single instance the heavy minerals make up by far the greater part of the non-clay minerals (Table 8). Because of these facts 2A5 is termed a pyritized shale.

The corresponding layer at Prospect Hill is the black fissile shale, 1A5, which also contains much pyrite (Table 3).

The layer above 2A5 is a thick bedded blue-gray shale, $2A8a_1$. The heavy minerals are again flooded with pyrite (Table 4). At Prospect Hill the corresponding member $1A8a_1$ has very little pyrite (Table 3). On inspecting mineral content of $1A8a_1$, however, we see that the pyrite once was present but has been converted to hematite and limonite.

It is suggested that the same type of conditions were in force at this time as the conditions outlined by Tarr as responsible for the pyritization of a local black shale occurring usually above the Bevier coal in Boone County, Missouri. This local shale can be placed, from its position and description as given by Tarr, as a counterpart of A5. The sea was shallow, "the first one to submerge the swamp after the coal was deposited." This is in accord with A5 and with Weller for, in the typical cyclothem, 5 is the first marine member.

The gray color of A8a is due to the fact that the sea was shallow enough to support bacteria which reduced the ferric compounds carried into the sea, into the ferrous state; hydrogen sulphide, formed from organic matter present, converted the iron to compounds producing the gray to blue colors. $1A8a_3$ is tan but this color change is due merely to oxidation in place for one can easily see when one examines 1A8a in place, that the gray color has been leached from the upper portion of 1A8a giving rise to $1A8a_3$. Samples were collected showing the gradual transition.

A8b and A8c were probably gray originally but have been oxidized to their present color.

When we pass over an uncomformity we should note mineral change. This is found if we disregard 2B1 and 1B1a which members have been derived in great part from the reworking of the upper portions of A8c and therefore should have the minerals of A8c.

At the end of A8c time the land rose out of the sea and a repetition of the above events took place. In other words Allen's theory is applied anew. That is, laterization formed once more a regolith composed of chert at the top ranging down through halloysite to kaolinite to illite. Only this period of kaolinization was not as long in duration as the corresponding erosion period at the base of cycle A for the fire clay of B is very thin

compared with the Cheltenham.

The process is the same as that of cycle A. The streams began to cut down into the members of cycle A and the streams carried the erosion products produced on the plains into the sea. Ozarkia, Appalachia, Llanoria and other upland areas were uplifted again and erosion was increased. Soon the broad streams became overloaded and began to migrate over the plains and to deposit sediment. In the beginning the sediment consisted of sandy clays or silts or sands as 1B1a. The sand of these shales came in great part from the chert on the top of the laterized surface. The clay mineral (illite, Table 1) came from the top of cycle A which was being eroded upon the plains by the streams. However, soon the streams were no longer cutting into illite bearing rocks but had become filled with sediment. In this stage 1B1b was deposited. The kaolin of the regolith began to be penetrated at this time and, as the streams no longer were cutting very much into illite, the clay mineral, illite, began to be replaced by kaolinite so that the clay mineral of 1B1b is kaolinite (Table 1).

Erosion began to cut into the regolith in earnest and the sand minerals became less. Kaolinite increased still more in the deposited sediment. Though highly kaolinized parts of the regolith contributed some halloysite, the lagoons were being formed by the streams impounding themselves, and member B2 was laid down. Conditions of deposition of member B3 were similar. Though this is as much of the section as was studied in the present investigation, subsequent events were much the same in B as in A. For example, after the fireclay B3 was deposited, the lagoon became swampy and a thin smut, as seen by Knight (p. 38) and the author, was laid down. From there the process continued.

From these results we see that Allen's theory for the origin of the Cheltenham holds for cycle A and also holds for cycle B. It is proposed that the theory can be applied to all cyclothems.

REFERENCES

ALLEN, V. T., *1937*, The Cheltenham clay of Missouri: *Mo. Geol. Surv. and Water Resour., 59th bienn. Rept.*, App. 5, pp. 1–29.

BECKER, HANS, *1931*, A study of the heavy minerals of the Pre-Cambrian Paleozian rocks of the Baraboo Range, Wisconsin: *Jour. Sed. Pet.*, vol. 1, n. 2, p. 94, Nov.

BUEHLER, H. A., *1907*, Lime and cement resources: *Mo. Bur. of Geol. and Mines*, vol. 6, 2d.s., p. 205.

GRAWE, O. R., *1923*, Septaria from the Pennsylvanian shale: *Wash. Univ. Stud., Sci. Ser.*, vol. 11, no. 1, p. 65.

GRAWE, O. R., and CULLISON, J. S., *1931*, A study of sandstone members of the Jefferson City and Cotter formations at Rolla, Missouri: *Jour. Geol.*, vol. 39, p. 309.

GRIM, R. E., BRAY, R. H., and BRADLEY, W. F., *1937*, The mica in argillaceous sediments: *Amer. Mineral.*, vol. 22, pp. 813–829.

KNIGHT, J. B., *1933*, The location and areal extent of the St. Louis Pennsylvanian outlier: *Amer. Jour. Sci.*, vol. 25, ser. 5, pp. 25–48, 166–178.

LARSEN, C. S., and BERMAN, H., *1934*, The microscopic determination of the nonopaque minerals: *U. S. Geol. Surv., Bull.* 848, p. 161.

TARR, W. A., *1928*, Syngenetic pyritization in local reducing areas of Pennsylvanian shales in Missouri: *Jour. Geol.*, vol. 36, n. 5, p. 436.

THIEL, G. A., *1935*, Sedimentary and petrographic analysis of the St. Peter sandstones: *Bull. Geol. Soc. Amer.*, vol. 46, p. 595.

TOLMAN, CARL, and KOCH, H. L., *1936*, The heavy accessory minerals of the granites of Missouri: *Contrib. In Geol. Wash. Univ. Stud.*, n. 9, pp. 11–50, Feb.

WANLESS, H. R., and WELLER, J. M., *1932*, Correlation and extent of Pennsylvanian cyclothems: *Geol. Soc. Amer. Bull.*, vol. 43, pp. 1003–1016.

WELLER, J. MARVIN, *1930*, Cyclical sedimentation of the Pennsylvanian period and its significance: *Jour. Geol.*, vol. 3, no. 2, p. 102.

REVIEW

C. B. BROWN. *The Control of Reservoir Silting. United States Department of Agriculture.* 1943. Misc. Pub. 521, 166 pp. (Government Printing Office, Washington, D. C. 25 cents)

For the past decade or more the Soil Conservation Service of the United States Department of Agriculture has been concerned with the problems resulting from accelerated erosion of cultivated lands and the manifold consequences of such erosion. Nothing other than the highest praise should be given to this work. One consequence of accelerated erosion is accelerated deposition in streams, over flood plains, and in lakes and artificial reservoirs. Losses of storage capacity due to such accelerated deposition in artificial reservoirs have been very large and represent serious losses of a natural resource, that is, areas suitable for construction of reservoirs. Thus, the appearance of a paper giving corrective measures is extremely welcome. The author is head of the Sedimentation Section, Division of Research, of the Soil Conservation Service. It is to be hoped that the paper will have wide distribution and will be carefully studied by those in charge of construction of future reservoirs, so that these are not constructed where excessive silting can not be prevented or controlled, and when construction is complete that provisions are made to prevent large losses of storage capacity due to silting.

The introductory part of the work under review presents a brief history of the construction of reservoirs and investigations of the problems of silting and the effects of silting in reservoirs constructed for different objectives, as water supply, irrigation, power, etc. Reservoirs constructed during the eighteenth century were small and were intended to provide water power for mills and small factories. The growths of cities in the early half of the nineteenth century led to greatly increased demands for water and many reservoirs were constructed to impound water for domestic and factory use and water for barge canals. Impounding reservoirs to provide water for hydraulic mining were built in California in the period from 1850 to 1870. Construction of reservoirs in the United States for irrigation was first done by the Mormons in 1871. Dams to regulate stream flow began to be built in the late 1700's. It is estimated that prior to 1900 there were not more than 2000 reservoirs in the United States of which the cost did not exceed $250,000,000. The great period of reservoir building in the United States belongs to the twentieth century and an inventory made in 1941 by the Soil Conservation Service records 8,900 dams and reservoirs constructed for larger uses, and in addition more than 3,800 others constructed for farm ponds, conservation purposes, and low power projects. The investment was placed at more than $4,450,000,000. Colorado seems at that time to have had the greatest number of reservoirs with California, New Jersey, and Pennsylvania not far behind. Louisiana, Maryland, Mississippi and North Dakota had few reservoirs. California and New York seem to have had the greatest investments. These reservoirs have been constructed for power, water supply, irrigation, navigation, maintenance of streams, flood control, and purposes of recreation.

Attention began to be given to the problem of silting after the middle of the nineteenth century, but efforts to combat silting were local and the problem seems to have received little serious general attention until after 1900 and since 1935 the Soil Conservation Service has made the problem one of very careful study.

The losses in storage capacity because of silting are extremely great and the author states that 21 per cent of the reservoirs of the nation which have been constructed for water supply will have a useful life of less than 50 years. Another 25 per cent will last 50 to 100 years, and 54 per cent will have storage capacity to meet present requirements 100 years from now. It is estimated that the value of the average annual loss in storage capacity is not less than $10,000,000 and that it may be as great as $50,000,000.

Control of silting is considered under the six heads of (1) selection of reservoir site, (2) design of reservoir, (3) control of sediment inflow, (4) control of sediment deposition, (5) removal of deposits made in a reservoir, and (6) control of erosion over the water shed, or drainage basin, supplying the reservoir.

Selection of a reservoir site is governed to some extent by the purpose for which the reservoir is intended, but in all cases studies of erosion of the land and suspended load of the entering waters should receive early consideration. There should be a suitable ratio between the inflow of water and the capacity of the reservoir to hold water. If the supply of water is very large compared to the capacity of the reservoir, silting is quite certain to be excessive. The storage capacity of a reservoir should range from a minimum of 75 acre-feet per

square mile of drainage area in the southern states to 250 acre-feet in the region of Texas to Oklahoma. If the storage capacity falls to less than 25 acre-feet per square mile of drainage area, it may be expected that silting will be excessive and storage capacity rapidly decreased because of so much water flowing through the reservoir and leaving therein its suspended and tractional loads. Many reservoirs have had very small ratios of storage capacity to watershed area. Lake Austin at Austin, Texas, had a storage capacity of only 0.84 acre-feet per square mile of drainage area and because of this small ratio it lost its capacity so rapidly that it was full of sediment after 13 years. The annual loss of storage capacity was 7.34 per cent. A more striking case is that of the water supply reservoir built on the Solomon River at Osborne, Kansas, in 1936 at a cost of $150,000. The storage capacity of this reservoir was only 0.14 acre-feet per square mile of drainage area. The reservoir was completely filled with sediment in one year. The prudent ratio of storage capacity to area of water shed should be such that there is a minimum of 100 years of useful life to a reservoir, that is, the rate of loss of storage capacity should be less than 1 per cent.

Control of inflow of sediment is one way of meeting the silting problem after the reservoir has been constructed. One method of doing this is the construction of settling basins above the reservoir. The idea is to trap the suspended and tractional loads of the inflowing waters before the reservoir is reached. This is an effective method until the settling basins have been filled. Filling of a settling basin may be rapid, as illustrated by the Mono Debris Dam on Mono Creek, California, above the head of the Gibralter Reservoir. This settling basin was completely filled with dominantly coarse sediments in the two seasons of 1936–37 and 1937–38.

A screen of vegetation along the inflow channels and over their flood plains is another device to trap sediments from waters before they enter a reservoir. Plants used for this purpose should be deep rooted, small stemmed, tough and fibrous, low growing, resistant both to drought and inundation and not liked by stock.

Silting may also be controlled by building a reservoir off-channel with a provision for admitting water after the water with an excessive load of sediments has been passed on. This may also be done by by-pass channels around a reservoir, or by conduits under it.

Deposition in a reservoir may be controlled to some extent by outlets through the dams by which waters with a higher than average load of sediments may be withdrawn. Several important reservoirs are said to have silting controlled to some extent in this way. Sediments produce density currents which seem to flow directly to the dam through the less turbid waters in a reservoir. This has been found to be the case in Lake Mead and it is possible that a properly placed outlet in the dam may remove these heavily laden waters from a reservoir. This method is still in the experimental stage.

Probably the most effective method of control of silting after a reservoir has been constructed is the control of erosion over the areas where the water falls. This can always be done in regions over which the fall of water is in such quantity and distribution as to make possible the growth of an adequate protective cover over lands with steep slopes. This growth should be protected against burning and overgrazing and cultivation practices on the cultivated lands over the watershed should be handled so that run-off is reduced to a minimum. Under these conditions the water enters the ground. Most reservoirs in humid regions owe the silting which takes place in them to unwise land use and improper methods of cultivation.

Finally, after silting of a reservoir has been accomplished, it is possible to remove the deposits, in whole, or in part, by excavation, dredging, draining and flushing, flood sluicing, and sluicing with controlled waters, all expensive operations.

The author of "The Control of Silting" has brought together in easily read style the data bearing on losses due to silting and the methods of control. The work should be read by all interested in the construction of reservoirs, the cultivation of the lands which supply the sediments which destroy storage capacity, and by those interested in storage of water for irrigation, power, water supply for municipalities, stream control and recreation. Lastly, the paper should be read by sedimentationists as it shows how rapidly sediments may be deposited under some conditions. While it is not likely that the conditions of erosion in the past were as intensive as they now are under present unwise land use and cultivation, it is probable that there have been times and places in the past where sediments were deposited at rates comparable to those now taking place in some reservoirs.

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

OFFICERS FOR THE YEAR ENDING MARCH, 1944

J. HARLAN JOHNSON
President
Golden, Colorado

HERCHEL L. DRIVER
First Past-President
Los Angeles, California

R. DANA RUSSELL
Vice-President
San Diego, California

HENRY V. HOWE
Second Past-President
University, Louisiana

H. B. STENZEL
Secretary-Treasurer
Austin, Texas

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

OFFICERS FOR THE YEAR ENDING MARCH, 1944

A. ROGER DENISON
President
Tulsa, Oklahoma

FRITZ L. AURIN
Past-President
Fort Worth, Texas

ROBERT W. CLARK
Vice-President
Los Angeles, California

ROBERT E. RETTGER
Secretary-Treasurer
Dallas, Texas

CAREY CRONEIS
Editor
Chicago, Illinois

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN